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RELEVANCE OF DATA ANALYTICS IN SUSTAINABLE FISHERIES MANAGEMENT: AN EVIDENCE-BASED STUDY

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ABSTRACT

Aim of the study

The value of fish resources to socioeconomic development is immense. However, there is growing evidence that loss of quality in the marine environments e.g. marine waters at sea and coastal freshwater zones is threatening the availability of livelihood resources e.g. fish resources evidenced by the dwindling fisheries resources that promote sustainable livelihood. Aware of this, several fisheries' institutions, governments, and local users have come up with several strategies to boost marine water environment management and promote sustainable fishing. Unfortunately, most of the initiatives have not fully managed to eradicate unsustainable practices e.g. marine water pollution, which leads to loss of wild catches and to unsustainable fishing practices.

Material and methods

Owing to this we use a mixed research methods approach involving a systematic literature review and field survey in Alappad to argue and present a case for governments and fishery management organizations to invest in data analytics as a new pathway that can give a comprehensive, near real-time view of both ocean resources and coastal fishing activities in light of the declining fish stocks and escalating environmental problems such as marine water quality loss due to pollution.

Results and conclusions

Findings documented that by using data analytics, governments and fisheries management organizations/individuals may respond more swiftly to external forces such as climate change, and marine water quality loss, and implement new policies and regulations thus promoting sustainable fisheries management. Local perspectives of coastal communities could also guide the best data analytics tool or method to be used.

Keywords: data analytics, marine environment, sustainable fisheries management, data-driven decision making, Alappad – India

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INTRODUCTION

Setting the trend: Marine water environment and complexity issues

The quality of the freshwater e.g. in rivers (Walega et al., 2022) and in marine water environment is key to the functioning of the marine system, translating into high biodiversity richness, ecosystem functioning, and the sustainable provision of marine goods and services (Stolte and Graneli, 2006). A number of studies related to ocean water quality monitoring demonstrate a significant positive relationship between marine species abundance, including fish, to high degrees of marine water quality (Karydis and Kitsiou, 2013). In addition, the functioning of key marine ecosystems, such as corals that are habitats to rare marine fish in the near-shore zones, depends on the water quality of a given marine zone (FAO, 2006; Walega et al., 2022). Several studies have also indicated that phytoplankton blooms in the marine environment are determined by the quality of the marine water environment based on key marine environment biological monitoring parameters and variables for marine water quality assessment and monitoring, including programs to monitor: temperature, salinity, water transparency, orthophosphate, total phosphorus, silicate, dissolved oxygen, chlorophyll, total nitrogen, nitrate, ammonium and nitrite, phytoplankton (total abundance, abundance, and major groups, bloom dominance) (UNEP, 2010; UNEP/MAP, 2011). According to the 2019 United Nations Statistics Report on Ocean Statistics and marine water quality, it was discovered that for instance, countries in the Caribbean with high marine water quality – including in the shorelines, deltas, and water column in the Galapagos – had a higher species richness than marine zones that are either polluted or experiencing high levels of eutrophication. To clearly put this into perspective, the attainment of SDG 14, sustainability of marine biodiversity, food chains, and resources such as fish are directly dependent on marine water quality (GESAMP, 2018; UN Environment, 2018).

To sustain marine water quality, global and regional stakeholders have initiated several governance frameworks and policies to manage marine water quality, including regional seas program in 13 regions, six (6) of which are managed by the United Nations Environment Programme (UNEP) such as the Mediterranean, the Black Sea, the Baltic Sea, Wider Caribbean, East Asian Seas (COB-SEA), South Asian Seas, North-East Pacific, North West Pacific, Red Sea and Gulf of Aden, South-East Pacific and Western Africa. These programs cover 18 regions of the world, with over 149 participating countries (UNEP, 2010; UN Environment, 2018). Among others, they focus on the monitoring of ocean activities that might have detrimental impacts on water quality, biota, and the entire marine system, for instance, marine shipping (Karydis and Kitsiou, 2013). Unfortunately, despite these initiatives and the recognition of the value of marine water quality, there is evidence that marine activities such as mining, transport, and coastal urbanization have compromised marine water environments through pollution and unsustainable extraction or destruction of resources (Akiwumi and Melvasalo, 1998). According to the 2020 Joint Group of Experts on Scientific Aspects of Marine Environment Protection (GESAMP) report on global pollution trends, it is clearly indicated that marine pollution has increased and worst of all, from 1975–2015 marine pollution levels have more than tripled in biodiversity hotspots including Eastern and Southern Asia, Africa and Central America (http://www.gesamp.org/), thus posing a high risk to the provision of marine food resources such as fish (Christiani et al., 2019) that is mainly sourced from the tropical seas and oceans (FAO, 2022). Unfortunately, in most of these communities, there has been little research on how such unsustainability concerns in the marine space could be addressed which might have several ramifications (GESAMP, 2020), for instance, for SDG2 related to hunger, as most coastal communities rely on marine resources such as fish (UN Environment, 2018). The present research aims to fill the gap by documenting how the nexus related to unsustainable fisheries concerns, partly due to increased marine water quality stressors (human activities), could be mitigated via data analytics. To clearly document this, we first dig deeper into the state of global fisheries, and the sustainability concerns therein.

Marine fishing and emerging issues

Global fish and aquaculture resources are critically vital for ensuring food security, health, and employment (Fujita, 2021). Fish, for instance, is an inexpensive source of protein and micronutrients for millions of people (Shephard et al., 2022). Around 17% of the world's total animal protein consumption is made up of fish, crustaceans, and mollusks, most of which are caught in the ocean (Christiani et al., 2019; FAO, 2022). Aquatic food consumption increased from 9.9 kilograms per person on average in the 1960s to a record-breaking 20.5 kg in 2019, before slightly declining to 20.2 kg in 2020 (FAO, 2022). Aquatic food consumption is anticipated to rise by 15% by 2030, reaching an average of 21.4 kg per person, as a result of rising incomes, urbanization, better post-harvest procedures, and dietary patterns (www.unctad.org). Therefore, in low-income countries where overall protein intake is low and diets are less varied, fish and shellfish are particularly crucial for reducing malnutrition defects (Christiani et al., 2019; FAO, 2022; Shephard et al., 2022). In addition, fishing is an indispensable livelihood source (D. Bradley et al., 2019); with about 660 million people depending directly or at least partially on fishing, aquaculture, or fish-related activities – these figures include subsistence and secondary sector workers, and their dependents (FAO, 2022). Increased engagement in fishing and fish-related activities has ballooned international trade in fisheries and aquaculture products thus boosting socioeconomic development (www.wef.org). According to the 2022 FAO report, fishing and aquaculture trade generated a record high of 165 billion USD in 2018 and 151 billion USD in 2020. With increased aquaculture production and an emphasis on sustainable fisheries, fishing activities and fisheries resources are projected to be a key component in reaching UN Sustainable Development Goals (UN, 2023), thus the need for continuous management of fisheries resources, fishing zones, and value chains (International Resource Panel, 2021).

Sustainable Fisheries Management and Emerging Sustainability Issues

According to the 2021 International Resource Panel Report, sustainable management of marine environment biotic resources such as marine fish is a crucial pivot in Agenda 2030; especially SDGs 1, 2, 3, 5, 10, 12, 13, and 14 (UN, 2023). A study by Nguyen and Tran (2023) in Vietnam observed that integrated sustainable fisheries management not only helps monitor migratory species such as oceanic tunas but also aids in the optimization of multispecies ecosystems and the management of multi-gear fisheries (Willis and Bailey, 2020). It is supported by extensive literature that sustainable fisheries management including maintaining and balancing fish stocks, reducing ecosystem pollution, and Illegal, Unreported, and Unregulated (IUU) fishing (FAO, 2022), among other things, not only offsets fishing-related trade-offs (Willis and Bailey, 2020) but also balances sustainability benefits in world fisheries (Lam et al., 2016; Payne et al., 2016; Nguyen and Tran, 2023). Unfortunately, recent studies have documented that the increasing quest for and trade in fisheries' resources beyond sustainable limits is threatening livelihoods and development targets (World Ocean Assessment, 2021). Due to overfishing, pollution, poor management, and other causes, the availability of fisheries' resources continues to decline. In 2019, 64.6 percent of fishery stocks were within biologically sustainable limits, which is 1.2 percent less than in 2017 (FAO, 2022).

Studies have recommended that in order to reverse this trend, concerted efforts are needed, bringing together all stakeholders and actors, especially the big fishing companies and dealers, into global sustainability frameworks (D. Bradley et al., 2019; World Ocean Assessment, 2021). However, big fishing companies and dealers are increasingly placing unprecedented pressure on freshwater and marine ecosystems in their effort to catch enough fish to meet the surging demand (Fujita, 2021). In addition, efforts to manage sustainable fishing and promote ocean stewardship are still hindered by a number of issues, such as a lack of accurate and actionable information (FAO, 2022), and a lack of resources on the part of many governments to process and analyze data on where, when, and what kinds of fish are being caught by fishing boats, as well as other human activity at sea (Global Fish Watch, 2023). Because the targeted species are now in short supply, it takes five times as much work (measured in kilowatt-hours) to catch the same amount of fish as it did in 1950 (Christiani et al., 2019). The ability of endangered ocean species to reproduce and maintain their population is seriously threatened by this shortfall, which also imperils the commercial prospects of fishing businesses (World Bank, 2022). In addition, establishing effective management practices and systems in the management of fisheries and the lack of data to quantify catches and determine the best fisheries' practices, especially in developing countries, limits fisheries from realizing the benefits that scientific assessment and management would bring (Singh, 2016; Fujita, 2021). Practices such as reduction in the fish fleet, especially in Asia, so far have not translated into more sustainable outcomes, for instance related to reduced ballast and release of toxic oils by fishing fleet (GESAMP, 2018) but rather proliferated into Illegal, Unreported, and Unregulated (IUU) fishing (FAO, 2022).

Why Data Analytics in Sustainable Fisheries Management is Needed Now and Not Later

The complexity in managing marine water environment and the resources, including fisheries, both at micro and macro levels requires the adoption of new fisheries management, technologies, and data reporting pathways, especially that the current methods – such as fish stock assessments that often use catch and landings records – have proved ineffective and problematic in reporting and representing the extent of fish effort, removal, and sustainability in diverse fishing zones with many users, species, and fishing zones (Shephard et al., 2022). In addition, existing fisheries data and the developed advanced tools (such as ocean digital tools, and remote sensing platforms and vehicles) are mainly used as small-scale pilots and experiments (D. Bradley et al., 2019).

We argue that these gaps in both the marine environment complexities and fisheries resources management could be leveraged by the use of data analytics. Several studies contend that even though balancing fishing interest and environmental sustainability, especially in the ocean fisheries and in poor fishing countries where the appetite for marine fishes and creatures such as tuna, salmon, anchovy, and shrimp has ballooned (D. Bradley et al., 2019) at an average of 3.2 percent annually between 1961 and 2016 is complex (Christiani et al., 2019; Fujita, 2021), the use of advanced data collection, processing, and interpretation techniques presents an untapped potential to the management of both inland and marine fishing resources and effort (FishWise, 2018). According to studies, stakeholders in the fishing industry in USA and Europe are already reaping socioeconomic benefits by integrating data analytics into all aspects of the value chain, including fishery management, detection and capture, processing, reporting, and surveillance and control (Fujita, 2021). According to the 2019 Annual Economic Report on the EU Fishing Fleet, the application of advanced analytics in fish operations and management has resulted in a reduction in operational variable costs for labor, repair, maintenance, running fish related businesses, and fuel from 77.2 to 66 billion USD since 2017. In reality, large-scale fishing enterprises globally might save more than $11 billion as a result of advanced analytics (Christiani et al., 2019). This impetus has partly led to the initiation of the 60 million USD five-year project named *The Audacious Project* aiming, inter alia, to catalyze and apply satellite big data and Artificial Intelligence to publicly map and visualize over one million industrial fishing vessels in the ocean at near real-time (Global Fish Watch, 2023).

In developing countries, most fisheries' managers and people are also increasingly becoming tech-savvy, and over the past few years, as technology advancements have boosted data availability, streamlined the deployment of information, and expanded data ingestion capabilities, positive attitudes toward algorithms have grown in popularity across industries (Ricard et al., 2012; Payne et al., 2016; Krishna and T., 2018; European Union, 2019; Rahul and Babu, 2019; Raj and Babu, 2019; Sasikala et al., 2019). There is also agreement that fisheries need to adopt cutting-edge technical solutions to maintain a sustainable trajectory while minimizing their environmental impact, since rules alone cannot eliminate overfishing and emerging marine ecosystem concerns such as pollution, and climate change (Jambeck et al., 2015; Lam et al., 2016). Greater national and international collaboration efforts using modern data analysis will help with the majority of issues, including catch reporting, trade information sharing, subsidies, tariff policies, and regulation enforcement (Froese et al., 2018). Fisheries and the public may also benefit from the increased use of advanced data analytics (Christiani et al., 2019).

Based on the insights above, it is noteworthy to contend that the value of advanced data analysis/data analytics techniques and their application in fisheries' management not only focuses on the primary sources of fish extraction in the marine and freshwater ecosystem but further extends to other components of the fish value chain including traceability of supply and demand chains, markets, restaurants and individual consumption patterns, behavior, and environmental concerns to manage the fisheries' systems, which are novel approaches to holistic fisheries management (D. Bradley et al., 2019; Christiani et al., 2019). The only lacuna is the lack of crisp studies, especially on where specific data analytics tools and methods could be applied in a given fishing ecosystem (Global Fish Watch, 2023) – which aspect/gap we aim to fill. To support this argument, we delve into the literature to identify the recent advances in data analytics in the fisheries sector, highlight the recent data analytics tools, and show how they are used in fisheries, highlighting the importance of informing fisheries managers on the best actions or interventions for sustainable resource extraction.

METHODS

This research used a mixed methods approach involving: (i) a systematic literature review, and (ii) a field survey which entailed conducting 58 interviews with fisherfolk in Alappad village in coastal Kerala to gain their perspectives on their knowledge of data analytics methods or tools, and how they could be/are relevant to their fishing operations in particular, and sustainable fisheries in general.

Inclusion/Exclusion Criteria for systematically reviewed literature

The initial step involved conducting a systematic literature review (SLR) of documents (articles) related to data analytics in fisheries' management. Systematic literature reviews engage repeatable analytical methods for secondary data collection and analysis (Piper, 2013). SLR synthesizes published literature and describes its cutting-edge aspects (Piper, 2013; Ferrari, 2015). Systematic literature reviews, originally known for medical research published in core clinical journals (Ferrari, 2015), are growing exponentially in other fields, as demonstrated by Merkert and Bushell, (2020). Although this is secondary research on computer-assisted searches, the exhibition of rigor is paramount in SLR (Piper, 2013). During the search for articles, we predominantly focused on papers from high-impact journals. We used Scopus and Science Direct databases.

We limited the search to 2021 and beyond for papers retrieved from Scopus, and 2023 for research articles retrieved from Science Direct. The search was limited to English in all databases and no subject area limitations were put on the results from Scopus and Science Direct. Exclusion criteria included non-English articles, studies unrelated to fisheries data analytics, and non-peer-reviewed sources. The search terms used with the main keywords in Scopus were "data AND analytics AND fisheries AND management", which generated 16 articles. In addition, the search term "how AND to AND collect AND fisheries AND management AND data" was used to retrieve 82 articles from Scopus. A total of 98 articles were generated from the Scopus database. Furthermore, the search term "methods for collecting fisheries data in India" generated 3564 searches without limitations. When the search was limited to only research articles and to articles published in 2023 and beyond, a total of 201 documents were retrieved from the Science Direct database. In total, we retrieved 299 documents.

We downloaded these articles as *.ris* from both Scopus and ScienceDirect databases and uploaded them in Covidence – a software application for managing and streamlining systematic reviews. We examined and screened the articles in Covidence. The screening of process entailed removing duplicated copies of articles, and for this, one document was automatically removed. Two reviewers independently screened articles and consensus was achieved in case of conflicting article choices. Of the 298 articles subjected to screening, 163 were excluded at the title and abstract screening stage, 12 studies excluded because they were not available in full text, and 18 articles were excluded at the full text review stage. A total of 105 articles passed the eligibility criteria featured in the PRISMA chart as presented in Figure 1, and these were included in the systematic review and subjected to data extraction using a predefined data extraction excel form (https://tinyurl.com/Extracted-Files).

The extracted data included study characteristics, for instance: title, author(s), publication year, goal/objective of the study, non-digital and digital fisher-

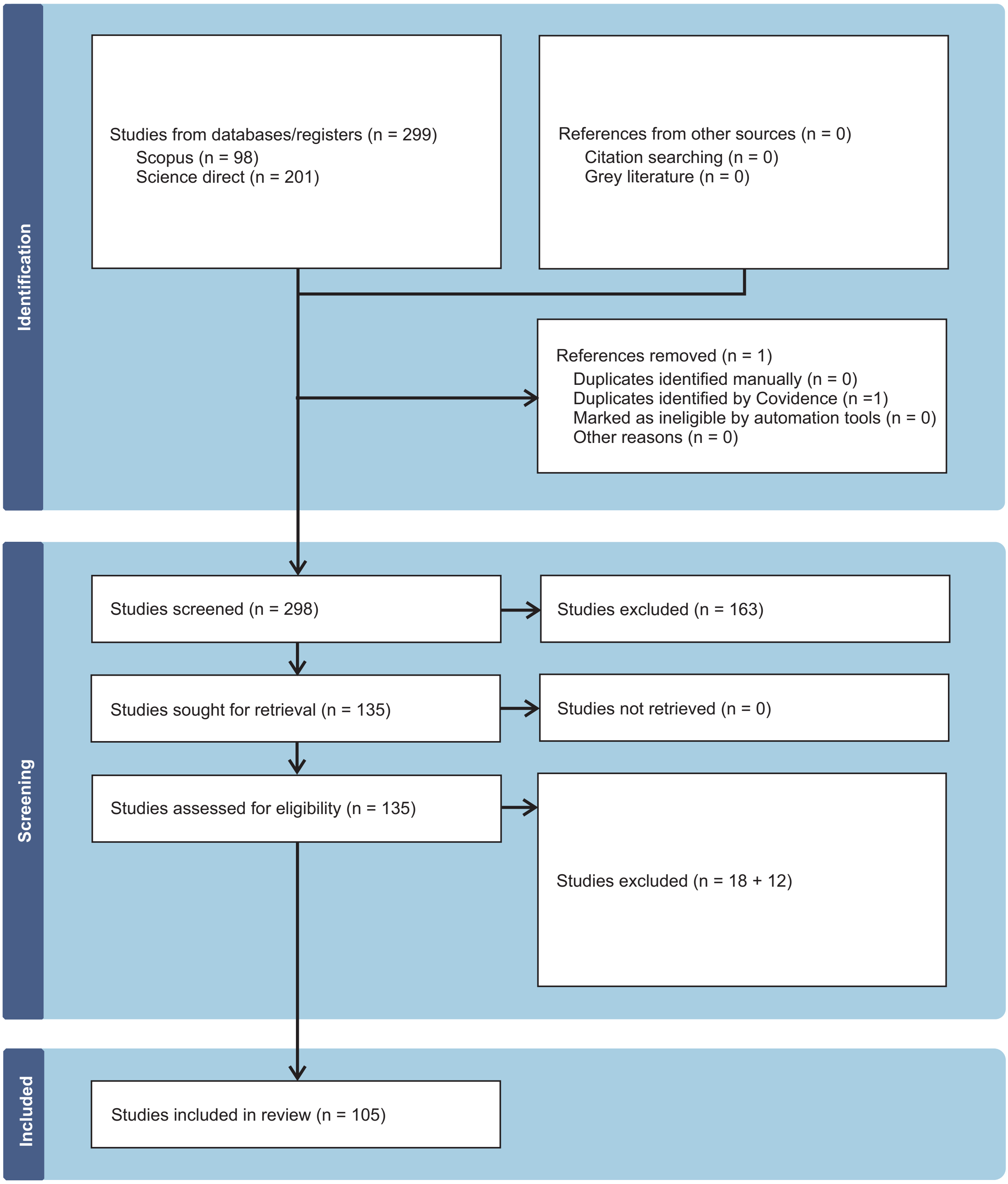

Fig. 1. PRISMA Chart showing the exclusion/inclusion criteria (source: elaborated by Authors)

ies data collection methods from the resource, data manipulation/management methods, country/area where the method was used as well as data analytics techniques employed and key findings in 'relevance of data analytics' column (https://tinyurl.com/Extracted-Files). Reviewers assessed quality and risk of bias of the studies that have been included in order to evaluate their methodological rigor, and any potential biases/disagreements were resolved through discussion.

To validate data from SLR, we conducted a field survey in the Alappad coastal community in Kerala, India. The survey involved participatory interviews with 58 fisherfolk engaged in coastal and deep-sea fishing. The purpose of the interviews was to gain an understanding of (i) the main methods used; (ii) fisherfolk's knowledge of modern fishing technologies such as drones; and (iii) their perspectives on whether such tools are key in promoting sustainable fisheries management.

Data Synthesis

Results from the selected studies were synthesized using a narrative approach, the key themes, and applications for data analysis/analytics in fisheries. The synthesis aimed to provide a comprehensive overview of the current state of fisheries data analysis and highlight its implications for sustainable fisheries management.

RESULTS

As noted in methods section, here we discuss the study findings in a coherent manner. We begin by giving an insightful description of data analytics, and the different data analytics methods. We present tools and software used in different fishing zones, while highlighting their feasibility in sustainable fisheries management. We then show the spatial distribution of the main fishing countries using data analytics, and lastly we discuss the relevance of the different data analytics tools and how they are relevant in sustainable fishing with a focus on different fishing zones, areas, and ecosystems.

Data Analytics in Fisheries

According to different scholars and literature, data analytics is the process of gathering, transforming (D. Bradley et al., 2019), and organizing data in order to make deductions, forecasts, and recommendations, and to guide well-informed decisions (Amorim et al., 2018). Data analysis and data analytics are sometimes conflated (Lam et al., 2016). These words are not precisely the same, but they are related. In actuality, data analytics is a subset of data analysis (Ricard et al., 2012) that focuses on gleaning insights from data whereas data analysis is broader and involves initial examination and interpretation (Estes et al., 2011). Data science (using data to theorize and forecast) and data engineering (creating data systems) are two more processes that are included in data analytics as a whole. Data analytics includes activities like predictive modelling, clustering, and optimization in addition to the application of statistical and machine learning approaches to long datasets (Christiani et al., 2019). In the context of fisheries management therefore, we can coalesce these definitions to denote that advancing data analysis/analytics could help both fisheries and fishery resource users symbiotically benefit (Froese et al., 2018) through increased data availability (Payne et al., 2016), better tools for communicating and deploying fishery-related information (Fujita, 2021), improved and efficient fisheries data ingestion (Jambeck et al., 2015), better decision-making on fisheries complexities on sustainability *vis-à-vis* profitability (FishWise, 2018), biological uncertainties, better monitoring, surveillance and reporting to fisheries managers (European Union, 2019).

In fact, several studies reveal that since the 1990s there has been increased focus on the need to science fishery-based management and stock assessments in order to promote good fishery performance, but the lack of data (D. Bradley et al., 2019), especially in small fisheries, impeded this target (Fujita, 2021). Additionally, a dearth of fishery data results in confusion about stock status, which raises the risk of overfishing and threatens the economic and food security of users who depend on that stock (D. Bradley et al., 2019; Global Fish Watch, 2023). This brought to the fore the need for data analysis and analytics as an integral part fisheries management (Lam et al., 2016). To leverage these benefits, a series of data analysis and analytics techniques and tools are used (Terracciano et al., 2020). Here, we document some of the advanced techniques and tools used in the context of sustainable fisheries management.

Main techniques and tools and how they are used

In order to better understand the data analysis/analytics context, here are some of the unique data collection tools, which were highlighted in the reviews:

Drones

Any aerial vehicle that uses software to fly autonomously or that may be controlled remotely by a pilot is referred to as a drone (Daley and Urwin, 2023). Numerous drones come equipped with cameras to gather visual data and propellers to stabilize flying paths (Lam et al., 2016). Drone technology is increasingly becoming incorporated into industries like videography, search and rescue, agriculture, and transportation (Lukambagire et al., 2022; NOAA, 2023). In the context of fisheries management, drones that are outfitted with cameras or other sensing equipment are being utilized more and more to study the ocean. Some even have the ability to navigate underwater (Mckee et al., 2020). Drones are more adaptable and less expensive than oceanographic vessels (Trudeau et al., 2021). They can also offer a more thorough sampling of the surroundings when delivered in groups (Inman et al., 2021). In fact, despite covering a smaller area than satellites, drones can produce more precise photos that enable the detection of tiny objects or events (European Union, 2019).

In addition, since different drones can fly at different altitudes and distances, small-scale fisheries and near-shore marine coastal fisheries can utilize very close-range drones, which can often reach up to three miles (Christiani et al., 2019). The range of close-range UAVs is about 30 miles. Drones with a short range may go up to 90 miles and are mostly used for spying and intelligence gathering (Daley and Urwin, 2023). Mid-range unmanned aerial vehicles (UAVs) have a 400-mile range and can be used for meteorological research (NOAA, 2023), marine scientific studies on species such as dolphins and sharks (Terracciano et al., 2020), and intelligence gathering (NASA, 2023).

The relevance of drones as key tools e.g. among artisanal fisheries was reported during the field survey (Table 1). Even though some fishers reported less familiarity with drones, certain key takeaways emerged, for instance, related to the acceptance of drones that could be a catalyst for promoting monitoring and locating of species to reduce fishing-related costs and harvesting of less targeted fishes. The local fisherfolk of Alappad further gave insights on the preferred type of drones, an insight that could be key in developing localized technological innovations for sustainable fisheries management.

Satellites

According to NASA (2023), a satellite is a moon, a planet, or an object in orbit around a planet or a star that serves primarily as a communications tool, transmitting things like phone calls and TV broadcasts around the globe (www.nasa.gov). Satellites can view enormous portions of the earth at once due to their eagle's eye perspective (Daley and Urwin, 2023). As a result, satellites are able to gather data more quickly and efficiently than devices on the ground (Copernicus Marine Environment Monitoring Service, 2023). In the sustainable fisheries management domain, we relate that satellites equipped with optical and radar sensors can provide an unprecedented level of spatial and temporal resolution (European Union, 2019), which makes them particularly useful for monitoring (Christiani et al., 2019; Gu et al., 2023). The electromagnetic spectrum's whole range of light reflected by the earth's surface is measured by optical sensors (NOAA, 2023). These data can be used to derive crucial oceanic metrics (Kemsley and Pukini, 2021) like water temperature and turbidity (Nguyen and Tran, 2023). Microwave radiation is emitted by radar sensors, which measure the amount that is reflected back to the device (NOAA, 2023). They can offer information about the topography of the water (Larson et al., 2021), winds, target species detection (Gilbey et al., 2021), and vessel movement (Fujita, 2021). Radar devices, unlike optical sensors, can gather data even in bad weather and lighting situations, such as when the sky is overcast or dark (Ricard et al., 2012).

Vessel onboard and underwater surveillance devices

These devices are mostly utilized in the detection, control, and monitoring of potential risks in marine areas (Terracciano et al., 2020). Unmanned robots, autonomous underwater vehicles, and unmanned underwater vehicles (UUVs) are a few types of equipment that can locate and identify dangerous and unsafe behaviors in marine environments (Christiani et al., 2019) such as the seabed (Terracciano et al., 2020). According to the US National Oceanic and Atmospheric Administration (NOAA, 2023), traditional ocean monitoring mechanisms were mostly laborious, involving the use of observers and manual recording onboard vessels, whereas new devices have bridged these gaps. For instance onboard sensors have the ability to automate and simplify this time-consuming procedure (Lee et al., 2021) while also producing more thorough and trustworthy data that may be included in platforms known as electronic monitoring systems (EMSs) (Terracciano et al., 2020). Additionally, tools like Vehicle Monitoring Systems (VMS) (European Union, 2019) and the Automatic Identification System (AIS) can gather data on a vessel's position (D. Bradley et al., 2019), speed, and direction (Copernicus Marine Environment Monitoring Service, 2023), supplement radar systems (Fujita, 2021), and reduce the likelihood of marine collisions (Christiani et al., 2019). Based on the evidence of the numerous advantages of emerging and advanced data collection tools and techniques shown above, we contend that data analysis/analytics has innumerable benefits related to sustainable fisheries management. As data analytics is a new paradigm shift (Amorim et al., 2018), one pertinent aspect that needs to be focused on is the spatial spread related to where or which countries and regions use some of these technologies in fisheries practices (Christiani et al., 2019; FAO, 2022), which trend we explore in the next section.

Scope of Spatial Use of Data Analytics Techniques in the Fisheries Domain

To underscore the value of data analytics, we visualized from the sourced literature which continents are increasingly adopting data analytics techniques in fisheries management and operations (Figure 2). Extracted

Table 1. Fisherfolk perspectives on the relevance of drones in fisheries management (source: Field survey in Alappad)

Themes	Subthemes
Familiarity with drones	Cognizant of the existence of drones but unaware or doubtful of using drones for fishing
Acceptance of drone technology used for fishing	Drones can aid in locating fish in the sea
	Drones can be used for search and rescue operations
	Drones can be used for mapping and monitoring mangrove forests
Doubts regarding using drones for fishing	Drones cannot catch fish using nets
	Fish are highly mobile and change location very quickly
	Drones can only spot fish on the surface of the water
	The sound of the drones will stop the fish from coming up to the surface
	Drones cannot cover large distances
	Drones cannot withstand harsh weather conditions
	Mapping breeding areas deep under the surface of the water is difficult
	Drones clash with traditional culture
Desired characteristics of a drone used for fishing	Ability to withstand any weather conditions
	GPS tracker
	Powerful camera
	Ability to detect fish deep beneath the water surface

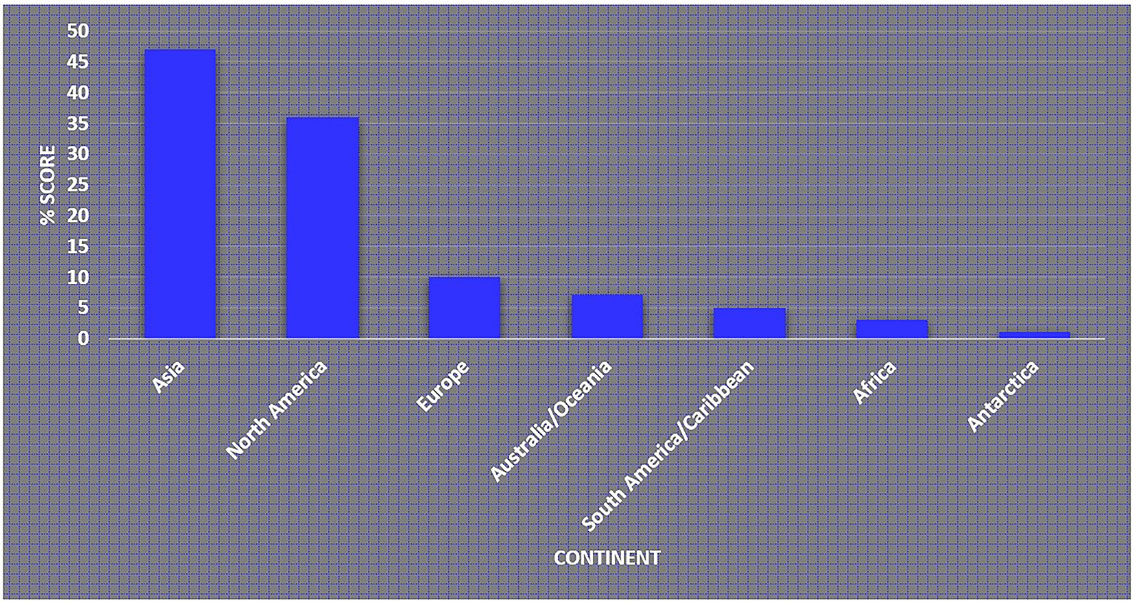

Fig. 2. A Bar Chart Representing Continental-wise Use of Data Analytics tools and methods (source: SLR Data)

results showed that Asian fishing countries are the most dominant (43%), followed by North America (33%), Europe (9.2%), Australia and Oceania (6.4%), South America and the Caribbean (5%), and ending with African (2.7%) and Antarctica fisheries (0.9%). We contend that the lower ranking of Antarctica is negligible due to less human settlement and fishing activity (UN-Habitat, 2023). The data shown in Figure 2 is pertinent as it reveals what is at stake in terms of fisheries management benefits to countries. A review of the 2022 FAO report documents that Asian countries such as China have not only continuously led global receipts emanating from fisheries, but also demonstrated sustained fisheries and aquaculture production compared to their peers in Africa. For instance, despite the devastating impacts of COVID-19 (WHO, 2023), Asian countries are leaders in fish and aquaculture production with the share estimated at 70 percent (FAO, 2022), as depicted in Figure 3.

At the same time however, increased fisheries' effort and production could also act as a tipping point for increased need for data analytics based on the number of fleet, and increased need for fisheries food/resources (FAO, 2017; Froese et al., 2018; Willis and Bailey, 2020). This was reported in Alappad where fisherfolk reported that 'drones could help in monitoring fishing activities e.g. around Mangrove zones'. Global estimates report an increase in fish effort with 75 percent of motorized and 95 percent of non-motorized fishing vessels operating in Asia and Africa respectively (FAO, 2022). The increase in fish effort could partly scupper sustainable fisheries' management due to increased and excessive effort (Global Fish Watch, 2023). Based on the complex evidence above, we hypothesize that countries/regions requiring sustainable fisheries production, and at the same time we refute the statement that negative shocks resulting from sustained fishing effort could leverage the immense benefits availed by data analytics.

Relevance of Data Analysis/Analytics

To show the relevance of data analysis and analytics in sustainable fisheries' management, we break down each data analytics technique to show which fishing ecosystem/zone or value chain (Table 2) it can be applied to among other coastal coral reef and offshore zones (Behivoke et al., 2021; Noelia et al., 2021), high seas (Midway et al., 2016), and in marine (Pitchandi and Balakrishnan, 2023), and freshwater species zones (Jaikumar et al., 2023; Muneer et al., 2023), so as to mitigate the myriad fisheries management challenges (FAO, 2022) such as marine

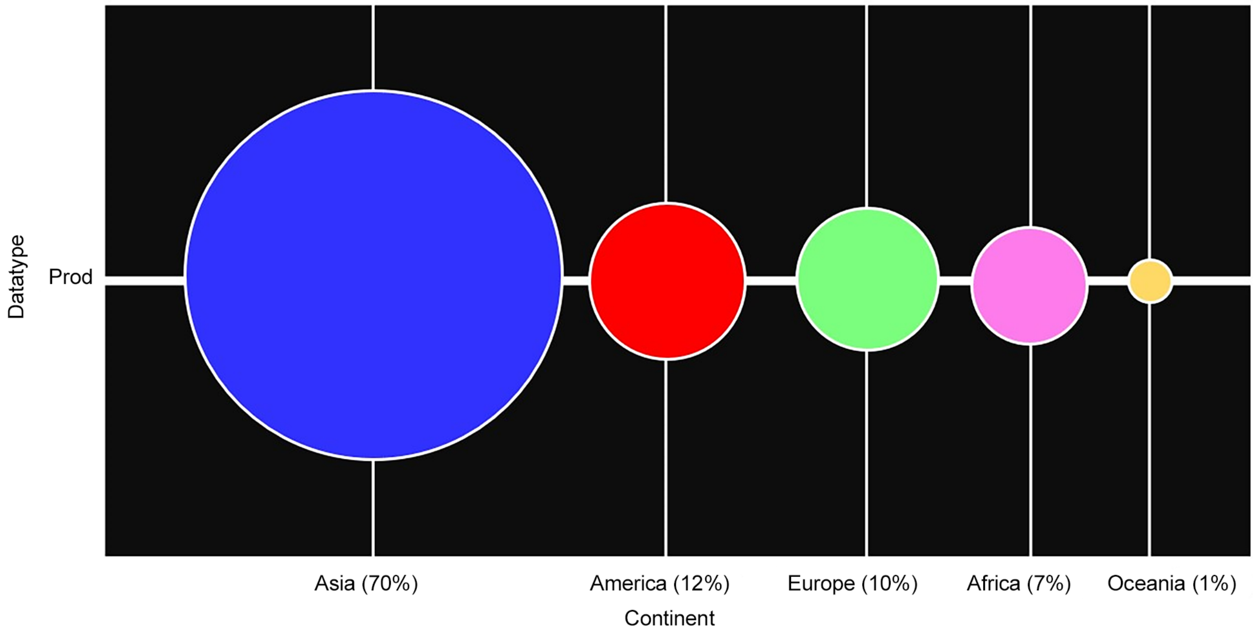

Fig. 3. A Bubble Chart Representing Continental-wise Fisheries and Aquaculture Production (source: FAO, 2022)

pollution (Goswami et al., 2023), fish supply chains (Mondragon et al., 2021), species stock assessments (Wang et al., 2022), IUU (Alessandrini et al., 2016), and sea grass assessments (Sebastian et al., 2023), among others.

Relevance in coastal and near-shore zones fisheries management

Coastal zones are a rich habitat for species and ecosystems (Wiltshire et al., 2018; Noelia et al., 2021) such as mangroves (Santoso et al., 2021), estuaries (Drenkard et al., 2021), sea grasses (Sebastian et al., 2023), and coral reefs (Behivoke et al., 2021; C.A. Bradley and Brown, 2021), among others, which not only provide fish resources but are crucial management zones (FAO, 2022). However, the increase in fish effort coupled with management gaps and IUU fishing (FAO, 2017, 2022; Pandion et al., 2023) are threatening the sustainability of such ecosystems as those of migratory species (C.A. Bradley and Brown, 2021). With this hindsight, there's growing evidence that advanced data processing techniques could be applied (D. Bradley et al., 2019).

Recent studies in the review revealed that data analysis/analytics techniques are relevant in coastal zones as they aid benthic species mapping using the Triplot of Redundnacy Analyses (RDA), Pearson correlation and big data, remote sensing, machine learning and Bathymetry LADS surveys in marine benthic zones, respectively (Wiltshire et al., 2018; Balachandar et al., 2023), decision making on species conservation and management using artificial intelligence models such as tray-based on machine learning, simple online and real time tracking algorithms in coastal aquaculture zones of China, univariate and multivariate statistics such as fixed Permutational Analysis of Variance PERMANOVA, Canonical Analysis of Principal Coordinates (CAP) in Marine Protected Areas (MPAs), coral and non-protected zones, and big data, remote sensing, machine learning, respectively (Noelia et al., 2021; Hellmrich et al., 2023; Xi et al., 2023), determination of salinity and surface temperatures in estuaries using the downscaling method, statistical and hybrid dynamical-statistical methods (Drenkard et al., 2021), segmentation of fishing vessel trajectories in coral reef zones using Global Positioning Systems (GPS) (Behivoke et al., 2021), determination of coastal fish vulnerability zones in the Indian Ocean using the mKRISHI Fisheries Analytic system and App (Singh, 2016), analysis of sea grass losses in near shore ecosystems, Island zones and

Table 2. Data analysis/analytics techniques, their relevance and where they are used (source: elaborated by Authors)

Data Analytic Method	Where is the method used	Relevance of Data Analytics	Author
Intelligent Analytics	River depth/River flow	Real time catchment regulation and water management	(Petri et al., 2018)
Big data, remote sensing, machine learning	Coastal and marine zones	Transforming enormous amounts of data for decision making	(Noelia et al., 2021)
Down scaling method; statistical methods and hybrid dynamical-statistical methods	Estuarine zones	Evaluation of salinity and estuarine surface temperature	(Drenkard et al., 2021)
Multiple simulation models and observational datasets	Red Sea	Ocean winds, weather forecasting	(Afzal et al., 2019)
Bayesian hierarchical methods	High sea	Analysis of trans-boundary fisheries	(Midway et al., 2016)
DBSIRM model – Big data analytics technology	Yellow sea	Fish index assessment and sustainable growth/development	(Wang et al., 2022)
LADS surveys - Bathymetry	Marine benthic species	Swath mapping, quantitative framework for spatial data management	(Wiltshire et al., 2018)
GPS tracking technology	Coral reef zones	Segmentation of vessel trajectories into fishing and non-fishing activities	(Behivoke et al., 2021)
PesKAAS application	Timor and Banda Sea	Providing near real-time information on catch and effort	(Tilley et al., 2020)
Predictive analysis, information fusion, and visual analytics	Dovar straight	Automatic identification of structural abnormalities, the prediction of vessel itineraries	(Alessandrini et al., 2016)
Predictive analytics and time series analysis	North Atlantic and Labrador Sea	Ocean monitoring, fish food supply chain and spot trends/decision making	(Mondragon et al., 2021)
Principal component analysis (PCA), cluster analysis	Deep Sea, cold coral zones, canyons	Assessment of potential habitat extent in the deep sea	(Bargain et al., 2018)
mKRISHI® Fisheries analytic system	Indian Ocean/ deep Sea-30km	Identification of risk zones in a fishery system	(Singh, 2016)
Geovisual analytics, Hybrid spatial temporal filtering (HSF) and automated behavioural change point analysis	Pacific and Atlantic ocean	Assessment of how well interactive and automated mapping solutions enhance fisheries enforcement efforts	(Enguehard et al., 2013)
Triplot of Redundancy Analyses (RDA) and Pearson correlation	Benthic zones	Assessment of morphological changes in benthic species	(Balachandar et al., 2023)

Data Analytic Method	Where is the method used	Relevance of Data Analytics	Author
Multivariate statistical analysis, Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA)	Fresh water ecosystems	Assessment of marine pollution and eutrophication in aquatic systems. Identification of distinct groupings of variables and understand the correlations between them	(Muneer et al., 2023)
AI to pattern analysis and information prediction	Fresh water ecosystems	Aquaculture improvement in small scale fisheries	(Jaikumar et al., 2023)
Log transformation, R, SPSS	Deep sea	Determining micro plastic pollution in zoo plankton	(Goswami et al., 2023)
Sensor information systems and data analysis using scatter plots for visualization	Arabian sea	Finding the enabling trends and insights in fish ecosystems and value chains	(Kishore et al., 2023)
Google Earth Engine (GEE), Regression plots	Near shore, Sea grass ecosystems and Island zones, and Arabian Sea	Multi-temporal analysis of Sea grass losses	(Sebastian et al., 2023)
Satellite photos	Coastal zones of India	Assessment of ocean acidification/ environmental, social, and governance-related	(Gu et al., 2023)
Non-parametric Kruskal-Wallis test, permutational multivariate analysis of variance (PERMANOVA)	Coastal mangrove ecosystems	Obtaining spatial temporal data on, and quantification of marine litter/ pollution in mangroves	(De et al., 2023)
Remote sensing and video surveillance devices	Indian coast/ Arabian Sea	Detecting spatial and temporal changes in beach ecosystems	(Ramesh et al., 2023)
Multivariate techniques, such as PCO analysis	Estuaries	Demonstrating spatial temporal changes in micro plastics pollution in fishes	(Jeyasanta et al., 2023)
Statistical data analysis, Pearson Product Moment Correlation analysis	Arabian Sea, Indian coast, Marine fish products	Estimating micro plastic presence in fishes	(Rukmangada et al., 2023)
SPSS software version 24 and Excel 2019, Shapiro-Wilk test, Pearson correlation tests	Persian Gulf	Understanding the concentration and marine plastics in fishes	(Esmaeilbeigi et al., 2023)
Machine learning methods Linear Regression, Random Forest (RF), and Support Vector Regression (SVR)	Benthic and coastal zones	Estimating water turbidity, chlorophyll (macro and micro algae)	(Ashphaq et al., 2023)
Principal Component Analysis (PCA) using R,	Native coastal and fresh water ecosystems/zones	Assessing climate change and species vulnerability	(Lianthuamluaia et al., 2023)

Table 2. cont.

Data Analytic Method	Where is the method used	Relevance of Data Analytics	Author
Pearson correlation, cluster analysis, and principle component analysis (PCA). For instance, cluster analysis	Ghana/Gulf of Guinea	Radiological evaluation of beach sediments and species risk	(Akuo-ko et al., 2023)
Multivariate analysis e.g. Pearson correlation, principal component analysis, and cluster analysis. Principal component analysis (PCA) and cluster analysis	Southeast Bay of Bengal	Estimating the health risk posed by consuming tainted seafood by giving useful insights into the distribution of heavy metals in the seafood	(Pandion et al., 2023)
RD-TFD and wordnet ontology features, tokenization, stopword removal, and stemming algorithms: Statistical metrics like precision, recall, F-measure, and accuracy	Marine ecosystems (Jelly fish clusters)	Analysing and grouping jelly fish clusters	(Pitchandi and Balakrishnan, 2023)
Artificial Intelligence (AI) models e.g. tray based on a deep-learning, simple online and real-time tracking algorithms	Coastal aquaculture zones/China	Making best technology and data driven decisions for sustainable prawn farm management	(Xi et al., 2023)
Univariate and multivariate statistics e.g. fixed permutational analysis of variance (PERMANOVA), Canonical Analysis of Principal Coordinates (CAP)	MPAs, Coral zones and non-protected zones	Comparing fish conservation and management policies in MPAs and non MPA zones	(Hellmrich et al., 2023)
Deep learning models and dimensionality reduction methods	Marine/Deep sea	Precise and effective monitoring of cetaceans (marine mammals)	(Boulent et al., 2023)
Machine learning and data mining method	Deep sea fishing vessels	Creating decision support tools in marine spatial planning / sustainable / harvesting	(Kelly et al., 2022)
Machine learning and computer vision techniques, Python, and Annotators	Marine ecosystems	Increasing understanding of long term stock fluctuations and environmental changes	(Bonofiglio et al., 2022)
R; REPHYTOX for data simulation	Marine and coastal areas	Informing management on scallops, effects of pollution, SST, and nutrient concentrations	(Chenouf et al., 2022)
Machine learning and statistical modelling solution - Haul biomass Index Estimator (HBIE)	High Sea	Filling gaps in trawl surveys	(Coro et al., 2022)
ArcGIS, Google Earth	Coastal marsh land zones	Analysing microplastic characteristics and distribution	(Wu et al., 2022)

Data Analytic Method	Where is the method used	Relevance of Data Analytics	Author
Visualization tools	USA coast	Obtaining insights into spatial dynamics of anglers' behaviour and fish populations	(Lant et al., 2022)
Isotope ratios, and Internet of Things (IoT)	Mediterranean coast	Identifying patterns and insights of sea food/ fish supply chains	(Palocci et al., 2022)
Remote sensing, modelling and sampling designs	Fresh water and riverine ecosystems	Shaping fish populations and ecosystems dynamics	(Torgersen et al., 2022)
Logistic regression model	Migratory Salmon Species / River estuaries	Sex identification of returning / spawning salmons	(C.A. Bradley and Brown, 2021)
Clustering analysis using R	East and South China Sea	Understanding mixed trawl fisheries characteristics and fishing habits of target species.	(Lee et al., 2021)
Bhattacharya technique, FISAT software and Barefoot Ecologist Toolbox	Java Sea	Understanding the spawning potential ratio of invasive species	(Santoso et al., 2021)
Generalised linear mixed model (GLMM)	Fresh water ecosystems	Estimating fish effort from remote traffic encounters	(Trudeau et al., 2021)

the Arabian sea using Google Earth Engine (GEE) and regression plots (Sebastian et al., 2023), detection and quantification of marine litter in mangrove zones using the Non-Parametric Kruskal-Wallis test and PERMANOVA (De et al., 2023), identification of changes in micro plastics pollution in coastal fish species in estuaries using multivariate techniques such as PCO analysis (Jeyasanta et al., 2023) and microplastic distribution in coastal marshlands using ArcGIS and Google Earth (Wu et al., 2022), radiological evaluation of the risk of species habituating along and in beaches such as crabs along the Gulf of Guinea using Pearson correlation, cluster analysis and Principle Component Analysis (PCA) (Akuoko et al., 2023), long-term understanding of species shocks and fluctuations due to environmental change using machine learning, computer vision techniques, Python, and Annotators (Bonofiglio et al., 2022), and obtaining insights into the spatial dynamics of fish anglers behaviour to fish populations especially along the US coast using visualization tools (Lant et al., 2022).

Some of the major breakthroughs in managing coastal pollution have been reported by studies conducted in estuaries in Tamil Nadu in India (Jeyasanta et al., 2023), in marshland zones (Wu et al., 2022), and in mangrove ecosystems in the Central West coast of India (De et al., 2023) that show geographic similarity patterns of microplastics in the water and sediment of the assessment sites across both seasons using multivariate techniques, such as PCO analysis (Jeyasanta et al., 2023). These studies helped in identifying the spatial variation differences in litter abundance among mangrove stands based on habitat characteristics, concentration differences as different locations and variation in litter abundance between mangrove floors and canopies based on location, for instance, by using PERMANOVA (De et al., 2023). The findings shed light on the effects of anthropogenic litter pollution on India's coastal mangroves, and they can be used to build efficient management measures to lessen these effects. The benefit of data analytics tools such as drones on monitoring mangrove ecosystems is also supported by field findings in Alappad (see: Table 1).

Relevance in deep-sea fisheries management

Deep sea fisheries are some of the most complex to manage, partly due to their presence in the 'global common' and the technicalities in monitoring high seas (FAO, 2022). Fortunately, recent advances in technology could help mitigate this gap (Christiani et al., 2019). Extracted documents revealed that data analysis/analytics techniques are increasingly being used to gather insights from the deep sea fishing challenges (European Union, 2019). For instance, multiple simulation models and observational datasets have been used in the Red Sea to monitor ocean winds, and weather forecasting (Afzal et al., 2019); Bayesian hierarchical methods are used in the analysis of transboundary fisheries (Midway et al., 2016); the DBSIRM model-a big data analytics technology is being used in the Yellow sea for fish index assessments, sustainable growth and development (Wang et al., 2022); the PesKAAS application has been used in the Timor and Banda sea to give near real-time information on fish catch and effort (Tilley et al., 2020); in the Dover straight, Alessandrini et al. (2016) used predictive analysis, information fusion and visual analytics for automatic identification of structural abnormalities in fishes and prediction of vessel itineraries; and Mondragon et al. (2021) used predictive analytics and time series analysis for ocean monitoring, food supply chain and spot trends in fisheries to inform decision making in Canada's North Atlantic and Labrador sea. Other breakthroughs in the deep sea include the assessment of potential habitat extent in deep-sea cold coral zones and submarine canyons using PCA and cluster analysis (Bargain et al., 2018). In the Pacific and Atlantic oceans, geo-visual analytics, Hybrid Spatial-temporal filtering (HSF), and automated behavioral change point analysis have been used to assess how well interactive and automated mapping solutions enhance fisheries enforcement efforts (Enguehard et al., 2013). In this study, the comparison of various methods for visualizing and examining movement data collected from Vessel Monitoring System (VMS) data was crucially emphasized. Making sense of the complicated and enormous VMS data sets requires the use of geo-visual analytics and other data analysis techniques. This knowledge can help with decision-making and enhance the management of fisheries resources.

In some regions, such as the Indian Ocean and Arabian Sea, log transformations have been used to determine microplastic pollution in zooplankton due to the increase in ocean gyres (Goswami et al., 2023). Other studies have used advanced methods such as statistical data analysis, and Pearson Product Correlation Analysis, in order to determine the amount of microplastics (Rukmangada et al., 2023) and to understand the concentration of microplastics in fishes, especially in the Persian gulf (Esmaeilbeigi et al., 2023). Sensor information systems applying scatter plots for visualization is used in the Arabian Sea to find enabling trends and insights in fish ecosystems and value chains (Kishore et al., 2023), and satellite photos are increasingly becoming relevant in the assessment of ocean acidification, environmental and social governance especially in the Indian ocean zones (Gu et al., 2023) as well as remote sensing and video surveillance devices to detect spatial and temporal changes in ecosystems (Ramesh et al., 2023). In the high sea benthic zones, machine learning methods e.g. Random Forest (RF), and Support Vector Regression (SVR) are used to estimate water turbidity, and chlorophyll (micro and macro algae blooms) (Ashphaq et al., 2023), and to precisely and effectively monitor marine mammals-cetaceans, especially in Canada (Boulent et al., 2023). This is done mainly by using a robust analysis of massive datasets of photographs of cetaceans combined deep learning models and dimensionality reduction methods, for instance, via the creation of a binary land cover map, thus creating a more effective and precise method of monitoring cetaceans thanks to the application of data analysis/analytics techniques. In the management of scallops and informing management on the scallop diversity and shocks due to the effects of marine pollution, Sea Surface Temperature (SST) changes, and nutrient concentrations, R and REPHYTOX for data simulation have come in handy (Chenouf et al., 2022).

In addition, to fill gaps in trawl surveys, machine learning and statistical modeling solution-Haul Biomass Index Estimator (HBIE) is used (Coro et al., 2022). A research conducted in the Adriatic Sea and around Italy, advanced spatiotemporal and environmental modeling tools were used to fill in the gaps in trawl survey data. These methods entail the evaluation of sizable data sets, including information on fish biomass, environmental factors, and survey hauls (Coro et al., 2022). Related to the above, a study conducted in the East and China Sea zone applied clustering analysis using R to understand mixed trawl fisheries characteristics and fishing habits of targeted species (Lee et al., 2021). For instance, in the area around Taiwan, the vast amount of data gathered from the mixed trawl fisheries in Taiwan is interpreted using clustering analysis to classify catch métiers and group fishing expeditions with comparable catch compositions. With this method, it is possible to comprehend mixed fisheries' characteristics and the fishing habits of various target species better. Additionally, a two-step methodology is employed to categorize pertinent clusters and pinpoint particular catch trends. Other advances in the deep sea domain have involved the use of the Logistic Regression Model to identify the sex of returning and spawning migratory salmons (C.A. Bradley and Brown, 2021; D. Bradley et al., 2019). In a study conducted in and around the River Yukon estuary in Canada, a morphometric model was created, applying logistic regression to determine the sex of Chinook Salmon that were returning to spawn. The fish's standard length (SL) and maximum eye diameter (MEF), as well as other demographic information, were used to create the model. The model was then put through a cross-validation evaluation and contrasted with other sex identification techniques (C.A. Bradley and Brown, 2021). The R statistical software suite was used to carry out each of these studies. In the Java Sea, the Bhattacharya technique, FISAT software, and Barefoot Ecologist Toolbox have been used to understand the spawning potential of invasive species (Santoso et al., 2021). In a study off the coast of Indonesia, these data analysis/analytics tools are utilized to analyze the information gathered about the length, weight, fecundity, and gonadal maturity of invasive crayfish in Java. The length data is specifically analyzed using the Bhattacharya technique, and the length at first maturity, selectivity capture, mortality fishing, natural mortality, and spawning potential ratio (SPR) are specifically analyzed using FISAT software. The SPR is also examined using the program from the Barefoot Ecologist Toolbox (Santoso et al., 2021). With the use of these data analysis/analytics techniques, it is possible to gain important insights on the biology and reproduction of invasive crayfish, which are crucial for foretelling how well they will integrate into Java's ecosystem and for creating long-term management plans.

Relevance in fishing vessels management

In the context of coastal and high sea fishing vessels management, a combination of data analytics methods have proved crucial (Christiani et al., 2019). For instance, for deep sea fishing vessels, machine learning and data mining methods have been used to create decision support tools in marine spatial planning and sustainable fish resource harvesting (Kelly et al., 2022). Several studies have reported that fishing fleet management requires the integration of substantial volumes of data from numerous sources, including vessel monitoring systems, automatic identification systems, and satellite photography (Christiani et al., 2019), and data analytics plays a significant role in this perspective (European Union, 2019). To find patterns and trends in fishing activity, stock abundance, and environmental conditions, the data can be examined using machine learning and data mining methods (Kelly et al., 2022), including tools such as drones (Daley and Urwin, 2023). This data is then employed to create decision support tools that can help with marine spatial planning, sustainable stock harvesting, and extensive fishing activity monitoring. Data analytics can also aid in identifying knowledge gaps and prioritizing research efforts to close those gaps. In addition, Singh (2016) proposed the mKRISHI fish analytic and system App for small fishing vessels around the Indian Ocean zone that can identify vessels risks and vessels under stress to about 30 kilometers offshore. The system streamlines the distribution of information about vessels, and ocean conditions/forecasts on ocean winds and waves to mobile phones in local languages, thus assisting fishers, their families, and other stakeholders in identifying risk zones, their occurrence date and time, and responding appropriately (Singh, 2016). Numerous fishermen are saved from death and risk exposure thanks to this data-driven strategy.

Relevance in freshwater ecosystems management

The relevance of data analysis/analytics transcends marine zones as research has demonstrated feasibility of their application in freshwater fisheries and ecosystem zones (D. Bradley et al., 2019). For instance, Petri et al. (2018) recommended the use of intelligent analytics for real-time catchment regulation and water management in river depth and river flow assessments. This can be done through the utilization of various data tools such as drones, and satellites (NOAA, 2023) to accurately predict river depth, river flow and rainfall up to five days in advance, which data is further analyzed and visualized to assess the risk and support informed decision-making related to regulating the catchment ecosystem (Petri et al., 2018). Based on this insight, we contend that data analytics plays a crucial role by providing the necessary insights and information to optimize catchment flow and conserve water resources. The ecological quality of freshwater ecosystems e.g. rivers are increasingly being threatened by eutrophication and pollution (FAO, 2022; Walega et al., 2022) and in this case, data analysis/analytics methods such as PCA, multivariate statistical analysis, and Hierarchical Cluster Analysis (HCA) could be leveraged to identify distinct groupings of pollution variables and understand correlations among them (Muneer et al., 2023). A study conducted to identify natural and/or anthropogenic sources of heavy metals and to aid in the interpretation of geochemical data in Lake Ahansar in India, multivariate statistical analysis was used by examining water quality metrics and heavy metal concentrations using PCA and HCA, which helped identify distinct groupings of variables and understand the correlations between them (Muneer et al., 2023). In freshwater aquaculture zones and farms, Artificial Intelligence using pattern analysis and information prediction has been used to boost the performance of small scale aquaculture fisheries (Jaikumar et al., 2023). A study by Jaikumar et al. (2023) focused on the application of AI to pattern analysis and information prediction for fish growers confirms this relevance. Freshwater ecosystems threatened by climate change and species vulnerability to climate change (Walega et al., 2022) have also been monitored through data analysis/analytics methods such as PCA using R. This was further confirmed in a study by Lianthuamluaia et al. (2023) in India, proving that data analysis/analytics is quite important after analyzing the data for water quality metrics over a period of 35 years using R software that helped in creating a database that can be applied for future conservation of other small native freshwater fish in South Asia.

Along riverine ecosystem zones, data analysis/analytics tools such as remote sensing, modeling, and sample designs are relevant in understanding ecosystem dynamics and shaping of fish populations. For instance, in the Riverscape study in the USA by Torgersen et al. (2022), data analysis/analytics was required to connect intricate patterns in heterogeneous data sets to ecological processes and forces that shape population and ecosystem dynamics, including using storage and geo-referencing to categorize the complexity of data analysis. Data analytics is thus a crucial instrument for comprehending patterns and processes in a management environment as well as for making defensible choices regarding the kinds of data gathering that will be aimed at being studied. This can further be utilized in the estimation of fish effort from remote traffic encounters, especially in over-fished freshwater ecosystem zones. A study in Canada by Trudeau et al. (2021) heavily relied on data analytics to estimate fishing activity throughout a fisheries landscape. To attain this, data from different sources, such as aerial surveys, creel surveys, and angler diary surveys was combined, using a generalized linear mixed model (GLMM) and also evaluating the precision of the model predictions using cross-validation techniques for estimating fishing effort based on lake features, nonparametric techniques such as random forests to account for nonlinear responses and interactions of lake characteristics. In areas that have coastal backwaters, this could be supplemented with the use of drones to monitor pollution levels and fish interactions in intertidal zones as reported from field findings.

Other fisheries-related management practices such as supply chain management and business

Since the 1990s global fisheries are increasingly being strained by the skyrocketing consumption and demand of both marine and freshwater species, especially in western markets (European Union, 2019;

FAO, 2022). This has not only led to increased fishing effort but also complex fish value chains (Christiani et al., 2019) dotted with IUU (FAO, 2022) and less regulation of fish trade value chains (FishWise, 2018). This requires the monitoring of value chains to trace the types of fish consumed, the nature of processing, and general fish standards (FAO, 2022). With this complex scenario, various data analysis/analytics techniques emerged as a bridge. An insightful research by Palocci et al. (2022), which aimed to identify patterns and insights of seafood and fish supply chains based on innovative data analysis/analytics tools, supports this argument. In their study in the Mediterranean Sea zone in Europe, they significantly observed that isotope ratios and the Internet of Things (IoT) is a feasible option to apply in identifying fish supply chains. They argued that, in order to manage, store, and analyze big data in a way that is useful for decision-making, new techniques are required using the 'search engine concept' as an alternative method for accessing and discovering data and metadata integration and analysis based on research inquiries about nutritional quality, food safety, authenticity, and transparency. Data analytics could therefore be very useful in this research because it can aid in the identification of patterns and insights from the vast volumes of data gathered from various food supply chains. In the Bay of Bengal, methods such as multivariate analysis including cluster analysis have been used to estimate health risks posed by consuming contaminated seafood by giving insights into heavy metal pollution in various species and kinds of seafood, for instance, via the use of stemming algorithms and RD-TFD, among others, to identify key traits in species using COA (Pitchandi and Balakrishnan, 2023).

CONCLUSION

In this paper we present the case for the relevance of data analysis/analytics techniques in sustainable marine water environment and fisheries' resources' management based on the current gaps in the current ecosystem related to sustaining and monitoring fisheries. It is evident from the review that most of the marine zones globally are experiencing unprecedented anthropogenic stressors, including increasing pollution in the near shore and inshore zones that affect fisheries resources and compromise marine water and resources quality and abundance, respectively (GESAMP, 2020). In addition, it is evident that in some jurisdictions, such as in North America and Europe, there is evidence of increased research and acknowledgement of the impact of unsustainable activities on marine water environment and the abundance of fisheries' resources and thus, most stakeholders are developing and increasingly using data analytics methods to bridge this gap (Christiani et al., 2019). Conversely, in developing countries, there is evidence that the use of these tools and methods of data analytics has not been fully harnessed, which could increase risks related to marine water pollution, loss of biodiversity and crucial resources such as fish (FAO, 2022). We explained the various data analysis/analytics methods and tools that are being advanced and can be leveraged in the fisheries management space. One notable aspect that came to the fore is that there is a discrepancy in the current use of data analysis/analytics where less developed regions are below par in adopting these technologies, which grossly affects sustainable practices and is likely to threaten livelihoods that rely on fishing.

We further described the relevance of data analysis/analytics techniques in coastal zones, freshwater zones, along the fisheries value chain, on vessels, and deep sea, by showing how each method can be used, and indicating the relevance of each method to the management of a given fish species, or a fishery zone. These evidences brought to the fore the case for data analysis/analytics in the fishing industry. We thus contend that by analyzing data from, for instance, using IoT sensors that offer information on vessel behavior, such as fuel consumption and navigational situations, data analytics could, for instance, give guidance on the efficiency use and management of vessel fuels and thus mitigate negative vessel impacts on the marine water environment, for instance, the release of oils that pollute fishing and fish breeding zones.

One notable observation and takeaway, especially among small scale fisheries and less tech-savvy fishing zones is that although there are immense benefits of data collection, processing, manipulation and visualization, fishing organizations and managers will not reach them by merely implementing sophisticated analysis/analytics projects. In addition, among coastal fisherfolk, local perspectives on the suitable data analytics tools and methods vary (as observed in the field findings in Alappad), which brings to the fore the need to integrate local knowledge and perspectives in promoting sustainable fisheries management. In addition, in some contexts, there is a need to completely restructure their fisheries management ecosystems and management pathways (European Union, 2019). For instance, employees who are involved in such transformations must possess the necessary skill sets such as species distribution modeling (SDMs) in addition to using the proper tools, procedures, and interfaces (such as dashboards with easy access to data). Furthermore, in the fishing value chain, business entities and fisheries operations dealers should train staff and offer assistance to ensure they understand the importance of sophisticated and advanced data analysis/analytics techniques and methods in the domain of fisheries management.

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Declaration of interest

Authors declare no conflict of interest.

Data Availability Statement

Data supporting reported results can be found in the shared Excel as supporting information and attached field data file.

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ZNACZENIE ANALIZY DANYCH W ZRÓWNOWAŻONYM ZARZĄDZANIU RYBOŁÓWSTWEM: BADANIE OPARTE NA DOWODACH

ABSTRAKT

Cel badań

Wartość zasobów rybnych dla rozwoju społeczno-gospodarczego jest ogromna. Istnieje jednak coraz więcej dowodów na to, że utrata jakości w środowiskach morskich, m.in. pogorszenie jakości wody w morzach i przybrzeżnych strefach słodkowodnych, zagrażają dostępności środków do życia, w tym zasobów ryb. Najlepiej świadczą o tym właśnie kurczące się zasoby ryb, stanowiące zrównoważone źródła utrzymania dla licznych społeczności. Mając tego świadomość, instytucje zajmujące się rybołówstwem, rządy i lokalni użytkownicy, opracowali strategie mające na celu usprawnienie zarządzania środowiskiem wód morskich i promowanie zrównoważonego rybołówstwa. Niestety w większości przypadków nie udało się w pełni odeprzeć i przeciwdziałać niekorzystnym praktykom, sprzecznym z zasadami zrównoważonego rozwoju, powodującym zanieczyszczenie wody morskiej, które prowadzi do uniemożliwienia tradycyjnych połowów i niezrównoważonych praktyk połowowych.

Materiał i metody

W związku z powyższym przyjęliśmy hybrydowe podejście badawcze, obejmujące systematyczny przegląd literatury oraz badania terenowe w Alappad, w celu opracowania i przedstawienia argumentów rządom i organizacjom zarządzającym rybołówstwem, aby inwestowały w analizę danych. Jedynie takie podejście jest w stanie zapewnić wszechstronny wgląd – praktycznie w czasie rzeczywistym – zarówno w zasoby oceaniczne, jak i działalność w zakresie rybołówstwa przybrzeżnego w świetle zmniejszających się zasobów ryb i nasilających się problemów środowiskowych, w tym utraty jakości wody morskiej, między innymi z powodu zanieczyszczeń.

Wyniki i wnioski
Badania jednoznacznie potwierdziły, że korzystając z analizy danych, rządy oraz organizacje i osoby zarządzające rybołówstwem, mogą szybciej reagować na czynniki zewnętrzne, takie jak zmiany klimatyczne i utrata jakości wody morskiej, oraz wdrażać nowe polityki i przepisy, promując w ten sposób zrównoważone zarządzanie rybołówstwem. Lokalna perspektywa społeczności przybrzeżnych może również pomóc w wyborze najlepszego narzędzia lub metody analizy danych.

Słowa kluczowe: analiza danych, środowisko morskie, zrównoważone zarządzanie rybołówstwem, podejmowanie decyzji na podstawie danych, Alappad – Indie