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Review

Anthropogenic impact on Indonesian coastal water and ecosystems: Current status and future opportunities

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ABSTRACT

Indonesia, the world's largest archipelagic country and the fourth most populated nation, has struggled with coastal water pollution in the last decades. With the increasing population in coastal urban cities, more land-based pollutants are transported to the coastal water and adversely affected the tropical ecosystems. This paper provides an overview of anthropogenic pollutant studies in Indonesian coastal water and ecosystems from 1986 to 2021. Nutrients, heavy metals, organic pollutants, and plastic debris are the most-studied contaminants. We found that 82%, 54% and 50% of the studies exceeding nutrients, heavy metals, and organic pollutants standard limit, respectively; thus, indicating poor water quality status in part of Indonesian coastal water. The coral reef ecosystems is found to be the most sensitive to anthropogenic disturbance. The potential effect of climate change, new coastal pollution hotspots in eastern Indonesia, marine anthropogenic sources, legacy/emerging pollutants, and the need for research related to the biological contamination, are discussed for future opportunities.

1. Introduction

Indonesia is the world's largest archipelagic nation with a territory that stretches from 6° N to 10° S and from 95° E to 142° E and comprises of 18,110 islands. Fig. 1 shows the five main islands of Indonesia: (a) Sumatera; (b) Java, the most densely populated island where the capital, Jakarta, is located; (c) Kalimantan which comprises two-thirds of the island of Borneo; (d) Sulawesi; and (e) Papua, which is part of the world's second-largest island, New Guinea. Two chain islands, Nusa Tenggara and Maluku, also hold significant historic and economic roles in the nation. Seventy-eight percent of Indonesian territories consist of water, and it has more than 81,000 km of coastlines that represent some of the world's most diverse tropical coastal and marine ecosystems. The Indonesian Sea is considered an ecosystem with high productivity due to seasonal upwelling and downwelling related to the monsoonal system, enhancing productivity at all levels of the food chain (Zijlstra et al., 1990). This region is located in the Indo-West Pacific center of biodiversity, which for the most part is comprised of three ecosystems: coral, mangrove, and seagrass. The eastern side of Indonesia is part of the Coral Triangle, the most biodiverse marine area on earth (Fig. 1). The Indonesian part of the Coral Triangle harbors over 75% of the world's coral species in 51,000 km^2 of coral reefs area (Asian Development Bank, 2014). The Indonesian's mangrove ecosystem is one of the largest globally, spanning over 33,100 km^2, accounting for over 20% of the world's mangroves (Giri et al., 2011). Indonesia also hosts over 30,000 km^2 total seagrass area throughout the Archipelago (Kuriandewa et al., 2003). In total, Indonesian mangrove forests and seagrass meadows hold 17% of the world's blue carbon reservoir (Kuriandewa et al., 2003; Alongi, 2014).

However, the Indonesian tropical coastal water and ecosystems are currently threatened by stresses associated with anthropogenic activities. Seventy-five percent of the nation's cities are located in coastal areas, and the coastal population encompasses 65% of Indonesia's inhabitants (Dahuri, n.d.), or approximately 160 million people. About 35

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million live in Jakarta, the Indonesian capital, and one of the 33 megacities in the world (United Nations, 2019). The Asian Development Bank (Asian Development Bank, 2016) reports that the Indonesian coastal water quality has been showing a steady decline, particularly in congested coastal cities of Java. Excessive nutrients, organic compounds, and heavy metals from domestic wastewater, industry, mining, agriculture, aquaculture, and solid waste represent by far the most significant source of coastal water pollution in Indonesia (Asian Development Bank, 2016). The same report reveals that only 59% of the population has access to improved sanitation, increasing the anthropogenic pressure on the local natural water system. As a typical tropical Southeast Asian country, Indonesia has a wet, humid climate and favorable hydrogeological conditions favoring ubiquitous terrestrial pollutant transport to the ocean (Burnett et al., 2007). Tropical streams and estuaries are generally more sensitive to ecosystem modification than temperate ones because of the limited capacity of tropical vegetative in retaining nitrogen (N). As a result, significant amounts of terrestrial pollutants can be transported to the coastal areas without attenuation (Downing et al., 1999).

The Indonesian Government has provided regulations and guidelines to prevent further degradation of coastal water quality and ecosystem. For example, the national decree Peraturan Pemerintah (PP) 22/2021 regulates the environmental standard limit for seawater quality, considering the following seascape: harbor/industry (Class 1), coastal tourism (Class 2), or marine biota (Class 3). However, the implementation of these regulations has been unsatisfactory, and therefore, the coastal water quality problem remains an issue for environmental managers (Wieriks, 2011). Indonesia is projected to experience substantial growth of 8% from 2020 to 2035, which translates to an additional 1 million people living within 50 km of coastline (Jakarta Bureau of Statistics, 2020). Indonesia has maintained steady economic growth since 2005 (World Bank, 2019), resulting in more people moving to the few big cities and widespread urbanization. Considering the current trends, it is expected that the additional stress on the coastal environment will continue, prompting for establishing the baseline of the current status and knowledge of Indonesian coastal water quality, particularly related to land-based pollutants from anthropogenic activities.

The aims of this paper are (1) to provide an overview of the current knowledge and status of the Indonesian coastal ecosystems and water pollution, and (2) to establish future guidelines for future studies, but also for authorities to implement restoration actions that would improve coastal water quality and ecosystem in Indonesia. We have compiled and reviewed the available literature and grouped the studies based on the four most-studied pollutants: (1) nutrients, (2) heavy metals, (3) organic pollutants, and (4) plastic debris/microplastics studies. We also mapped the distribution of research locations related to this topic throughout the Indonesian Archipelago. We limited the scope of our study to: (a) studies measuring chemical/microbiological contaminants from human activities, (b) studies measuring environmental and health impact of anthropogenic contaminants, not social or economic impacts, (c) studies measuring coastal water, sediments, coral reef, mangrove, and seagrass, not marine biota, and (d) studies written in English. We discuss future challenges and opportunities that can be implemented to understand Indonesian coastal water better and can be used by local researchers and governmental agencies to improve water quality and ecosystems' status.

2. Methods

This extensive literature study was performed by searching for keywords “Indonesia”, “coastal water quality”, “coastal water ecosystems”, “estuaries”, “bay”, “anthropogenic pollutants”, “anthropogenic contaminants”, “nutrients”, “organic pollutants”, “heavy metals”, “fecal bacteria”, “plastic debris”, “microplastics”, and “radionuclides” in the Web of Science (https://www.webofknowledge.com/). The Web of Science results were imported to R (R Core Team, 2020) and analyzed with the Bibliometrix package (Aria and Cuccurullo, 2017). A total of 126 articles were found published between 1986 and 2021, with an average citation of 18 per document. Our database consists of 122 scientific articles, one proceeding paper, one editorial, and three reviews. Within this period, we identified an increasing trend of the annual scientific production of 6.9% (Fig. 2A). Of the total peer-reviewed science articles, 33 articles (25%) were written by local institutions (intra-country collaboration), while the rest of the articles were co-authored with foreign institutions or produced without Indonesian co-authorships. Germany (27 articles, or 21% of all papers) is the country with the most authorship collaboration with Indonesian scientists.

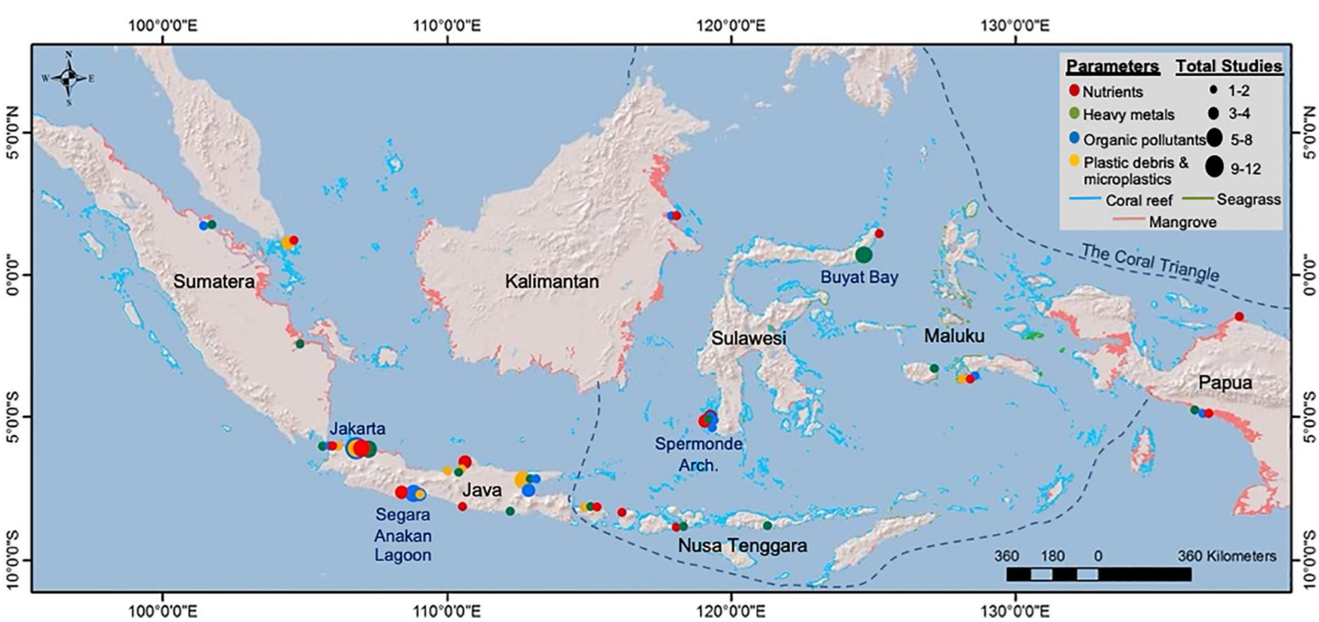

Fig. 1. Map of Indonesia, including the distribution of reviewed studies overlaid by the coral reef, mangrove, and seagrass ecosystems. Coastal ecosystem map was collected from Badan Informasi Geospasial (Badan Informasi Geospasial, 2014).

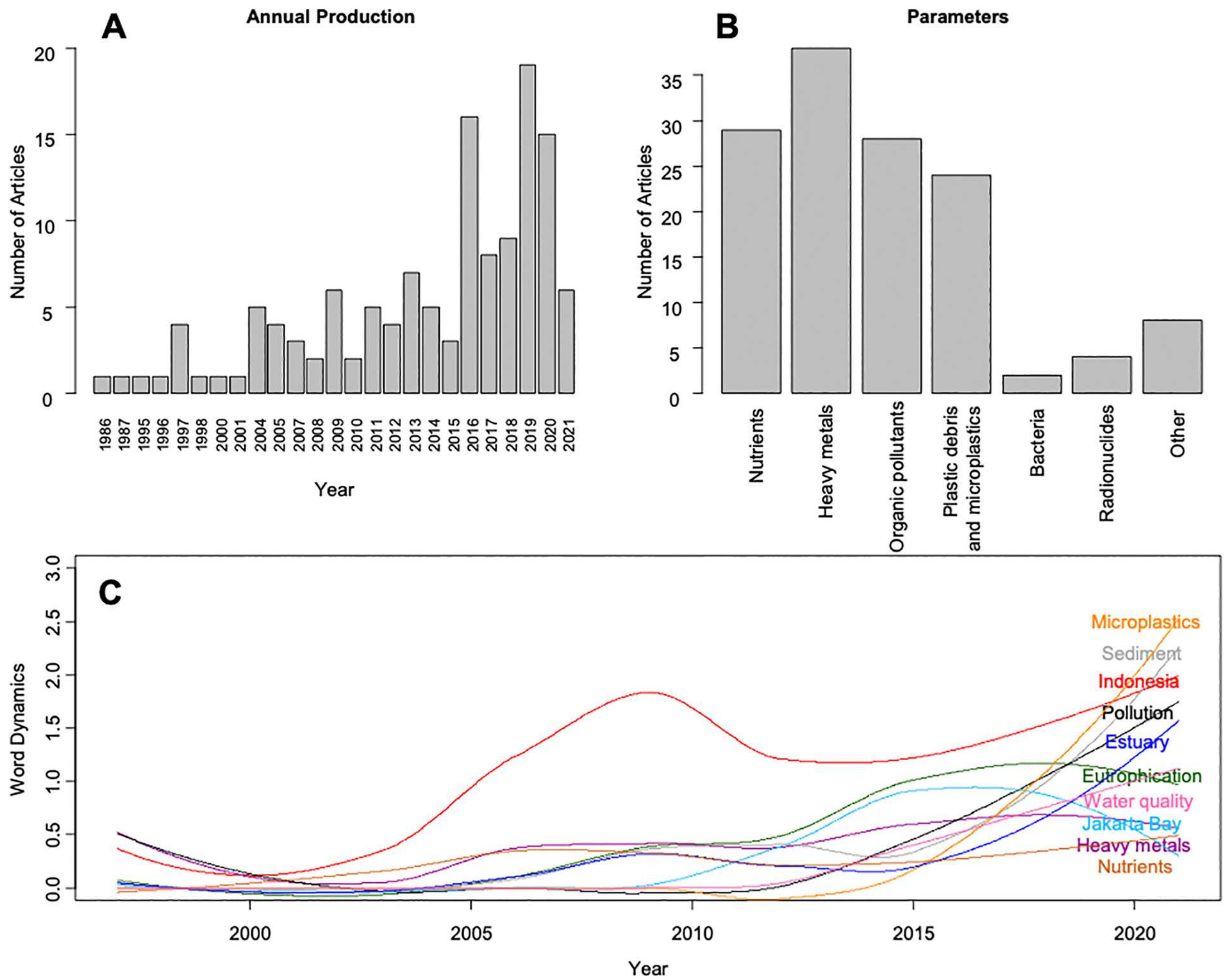

Fig. 2. (A) Annual scientific production from 1986 to 2021, (B) The quantity of pollutant-specific studies in Indonesian coastal water and ecosystem, and (C) Top 10 keyword trend analysis from 1997 to 2021.

3. Anthropogenic contaminations in Indonesian coastal water and ecosystems

Table 1 summarizes studies reviewed in this paper, while Supplementary Table provides detailed information about the studies. Half of the studies are concentrated on the Island of Java (55%), followed by Sulawesi (Fig. 1). Out of the 69 studies implemented in Java, 49% of them are conducted in Jakarta Bay. The mangrove and coral reef systems are the most-studied ecosystem with 10% of the reviewed articles. The mangrove ecosystem is predominantly studied in Segara Anakan Lagoon in southern Java. Coral reef studies are primarily conducted at the Spermonde Archipelago, which is part of the Coral Triangle in Sulawesi, and the Thousand Islands (Kepulauan Seribu), a reef ecosystem located in the northern Jakarta Bay, Java. Ninety-eight percent of papers we examined are based on field studies, with the remaining 2% employ modeling as their main approach. Based on specific pollutants we described in this paper, most of the research focuses on heavy metals as their primary parameter to measure (30%), followed by nutrients (23%), organic pollutants (22%), and plastic debris/ microplastics (19%) (Fig. 2B). A top 10 keyword analysis suggests that microplastics are the pollutant with the highest increasing trend of published studies in the last five years (Fig. 2C). Nutrient-related research, which is usually connected to eutrophication, is also consistently prevalent. However, heavy metal-related studies display a downward trend since 2018. Throughout this review paper, the terms "nutrients, heavy metals and organic compounds" will be used when referring to the excess of these materials in the environment.

3.1. Nutrients

Nitrogen (N) and phosphorus (P) are two nutrients often correlated with water quality and health problems in the coastal water system. While N and P are naturally found in the environment, elevated concentration of N and P or their deviations from Redfield ratio (16:1) in coastal and marine water are often associated with eutrophication, harmful algal blooms (HABs), and changes in phytoplankton assemblage (Geider and La Roche, 2002). Terrestrial anthropogenic N and P pollutions usually originate from agricultural or aquacultural activities, residential and industrial wastewater production, or burning fossil fuel (Withers et al., 2014). The national decree PP 22/2021 regulates N (as nitrate (NO_3-N) and ammonia (NH_3−N)) and P (as phosphate (PO_4-P) and total P) in Indonesian coastal and marine water (Table 2). Of the 22 nutrient-related field studies we reviewed, 82% of the studies show a violation of these parameters, suggesting alarmingly poor water quality status in Indonesian coastal water (Supplementary Table).

A modeling study of the 19 major Indonesian rivers concludes that dissolved inorganic nitrogen (DIN) fluxes have increased by 145% in the period between 1970 and 2000 due to intensive fertilization (Suwarno et al., 2013; Suwarno et al., 2014). In comparison to other sites, Java is the hotspot for coastal nutrient pollution in Indonesia (Fig. 3). Studies show that a combination of natural (e.g., coastal morphology) and anthropogenic causes influence nutrient concentration in coastal water. For example, a high DIN concentration up to 271 μM or equivalent with 3.8 mg L^{-1} was observed in southern Java (Fig. 3), attributable to the karstic geology of the area. In his review of the coastal pollution trend in

Table 1
Summary of the studies reviewed in this paper.

Study sites (island, location)	Reference
Nutrients	
Java, Jakarta	(Arifin et al., 2004; van der Wulp et al., 2016a; Hayami et al., 2020; Ladwig et al., 2016; Damar et al., 2019; Damar et al., 2020; van der Wulp et al., 2016b; Baum et al., 2015; Baum et al., 2016a; van der Meij and Hoeksema, 2010; Cleary et al., 2016)
Java, Jepara	(Adyasari et al., 2018; Adyasari et al., 2019a; Maslukah et al., 2019; Maslukah et al., 2021)
Java, Banten	(Booij et al., 2001)
Java, Yogyakarta	(Oehler et al., 2018)
Java, Segara Anakan Lagoon	(Nordhaus et al., 2009; Nordhaus et al., 2019; Jennerjahn et al., 2009)
Java, Porong	(Sari et al., 2021)
Sumatera, Bintan	(Syakti et al., 2019a)
Nusa Tenggara, Lombok	(Oehler et al., 2019)
Nusa Tenggara, Bali	(Marion et al., 2005)
Kalimantan, Berau	(Van Katwijk et al., 2011)
Sulawesi, Spermonde Archipelago	(Teichberg et al., 2018; Nasir et al., 2016; Sawall et al., 2011; Ambo-Rappe, 2014)
Sulawesi, Bitung	(Baohong et al., 2016)
Maluku, Ambon	(Likumahua et al., 2020; Likumahua et al., 2019)
Papua, Mimika	(Alongi et al., 2013; RHR and Hamuna, 2019)
Papua, Bismarck	(Muchtar, 2004)
Various locations	(Suwarno et al., 2013; Suwarno et al., 2014; Sidharta, 2005; Edinger et al., 1998)
Heavy metals	
Java, Jakarta	(Arifin et al., 2004; van der Meij and Hoeksema, 2010; Riani et al., 2018; Sindern et al., 2016; Williams et al., 2000; Hosono et al., 2011; Siregar et al., 2016; Rachello-Dolmen and Cleary, 2007)
Java, Banten	(Booij et al., 2001)
Java, Segara Anakan Lagoon	(Syakti et al., 2015)
Java, Semarang	(Takarina et al., 2004)
Java, Surabaya	(Titah and Pratikno, 2020)
Sumatera, Dumai	(Amin et al., 2009a; Amin et al., 2009b)
Nusa Tenggara, Bali	(Suteja et al., 2020)
Nusa Tenggara, Flores	(Nienhuis, 1986)
Nusa Tenggara, Sumbawa	(Angel et al., 2013)
Sulawesi, Spermonde Archipelago	(Ambo-Rappe, 2014; Analuddin et al., 2017)
Sulawesi, Buyat Bay	(Lasut et al., 2010; Limbong et al., 2005; Edinger et al., 2008; Edinger, 2012; Edinger et al., 2007; Blackwood and Edinger, 2007; Prisetiahadi and Yanagi, 2008)
Sulawesi, Makassar	(Najamuddin et al., 2016)
Maluku, Buru Island	(Male et al., 2013; Reichelt-Brushett et al., 2017)
Papua, Mimika	(RHR and Hamuna, 2019; Brunskill et al., 2004; Alonzo et al., 2016; Tanjung et al., 2019; Morrison and Delaney, 1996)
Various locations	(Scott and Davies, 1997)
Organic pollutants and micropollutants	
Java, Jakarta	(van der Wulp et al., 2016b; Williams et al., 2000; Dsikowitzky et al., 2020; Dsikowitzky et al., 2014; Dsikowitzky et al., 2016a; Dsikowitzky et al., 2017; Dsikowitzky et al., 2016b; Dsikowitzky et al., 2018; Dsikowitzky et al., 2016c; Koike et al., 2012; Baum et al., 2016b)
Java, Banten	(Booij et al., 2001)
Java, Segara Anakan Lagoon	(Syakti et al., 2013; Dsikowitzky et al., 2011; Ghozali et al., 2017) (Bouhroum et al., 2019)
Java, Surabaya	(Ilyas et al., 2011)
Java, Porong	(Jennerjahn et al., 2013; Sidik et al., 2016; Kure et al., 2014)
Sumatera, Dumai	(Liebezeit and Wöstmann, 2009)
Kalimantan, Berau	(Booij et al., 2012)
Sulawesi, Makassar	(Noor et al., 1987)
Maluku, Ambon	(Evans et al., 1995)
Papua, Mimika	(Alongi et al., 2013)
Various locations	(Harino et al., 2012; Sudaryanto et al., 2005; Hidayati et al., 2021; Alongi et al., 2009)
Plastic debris and microplastics	
Java, Jakarta	(Cordova et al., 2020a; Cordova et al., 2020b; Willoughby et al., 1997; Uneputty and Evans, 1997a; Cordova and Nurhati, 2019; Sembiring et al., 2020; Cordova et al., 2021)
Java, Semarang	(Khoironi et al., 2020)
Java, Surabaya	(Cordova et al., 2019; Firdaus et al., 2020; Kurniawan and Imron, 2019a; Kurniawan and Imron, 2019b; Lestari et al., 2020)
Java, Banten	(Falahudin et al., 2020)
Java, Demak	(van Bijsterveldt et al., 2021)
Java, Cilacap	(Bouhroum et al., 2019; Syakti et al., 2017)
Sumatera, Bintan	(Syakti et al., 2018; Syakti et al., 2019b)
Sumatera, Palembang	(Purwiyanto et al., 2020)
Nusa Tenggara, Bali	(Suteja et al., 2021)
Maluku, Ambon	(Uneputty and Evans, 1997b)
Various locations (review)	(Lestari and Trihadiningrum, 2019; Purba et al., 2019)
Fecal and pathogenic bacteria	
Java, Jepara	(Adyasari et al., 2019b)
Sulawesi, Spermonde Archipelago	(Kegler et al., 2017)
Radionuclides	
Java, Jepara	(Adyasari et al., 2018; Adyasari et al., 2019a)
Java, Demak	(Muslim et al., 2017)
Nusa Tenggara, Lombok	(Oehler et al., 2019)
Various locations	(Suseno and Prihatiningsih, 2014; Suseno and Wahono, 2018; Suseno et al., 2017)

Table 2
Summary of nutrients, heavy metals, organic pollutants, bacteria, and radionuclidesparameters regulated by PP 22/2021 for seawater quality (Class 3/ marine biota).

Parameter	Maximum limit
Ammonia (as NH_3-N)	0.3 mg L^{-1}
Ortophosphate (as PO_4-P)	0.015 mg L^{-1}
Nitrate (as NO_3-N)	0.06 mg L^{-1}
Polycyclic aromatic hydrocarbons (PAH)	0.003 mg L^{-1}
Polychlorinated biphenyls (PCB)	0.01 μg L^{-1}
Phenols	0.002 mg L^{-1}
Pesticides	
- BHC	210 μg L^{-1}
- DDT	2 μg L^{-1}
- Endrin	4 μg L^{-1}
Tributyl tin (TBT)	0.01 μg L^{-1}
Mercury (Hg)	0.001 mg L^{-1}
Chromium VI (Cr(VI))	0.005 mg L^{-1}
Arsenic (As)	0.012 mg L^{-1}
Cadmium (Cd)	0.001 mg L^{-1}
Copper (Cu)	0.008 mg L^{-1}
Lead (Pb)	0.008 mg L^{-1}
Zinc (Zn)	0.05 mg L^{-1}
Nickel (Ni)	0.05 mg L^{-1}
Fecal coliform	0 cell/100 mL
Total coliform	1000 cells/100 mL
Pathogenic bacteria	0 cell/100 mL
Any radionuclide	4 Bq L^{-1}

Jakarta Bay, Arifin (Arifin et al., 2004) indicates that land-based river input and monsoon current played a key role in the spatial and temporal variability of the N species in the bay. A long-term coastal water data indicates that annual means of DIN and PO_4 concentration increased 69% and 56%, respectively, between 2001 and 2019 (Fig. 4). Note that all PO_4 concentrations were above the environmental standard limit. The total N fluxes to Jakarta Bay are estimated between 40 and 174 tons/day while P fluxes and 14 to 60 tons/day, respectively, or equivalent to 0.1% and 0.5% of total global N and P export the ocean (van der Wulp et al., 2016a; Sharples et al., 2017). The measured nutrient concentrations in Jakarta Bay are either higher or comparable to other

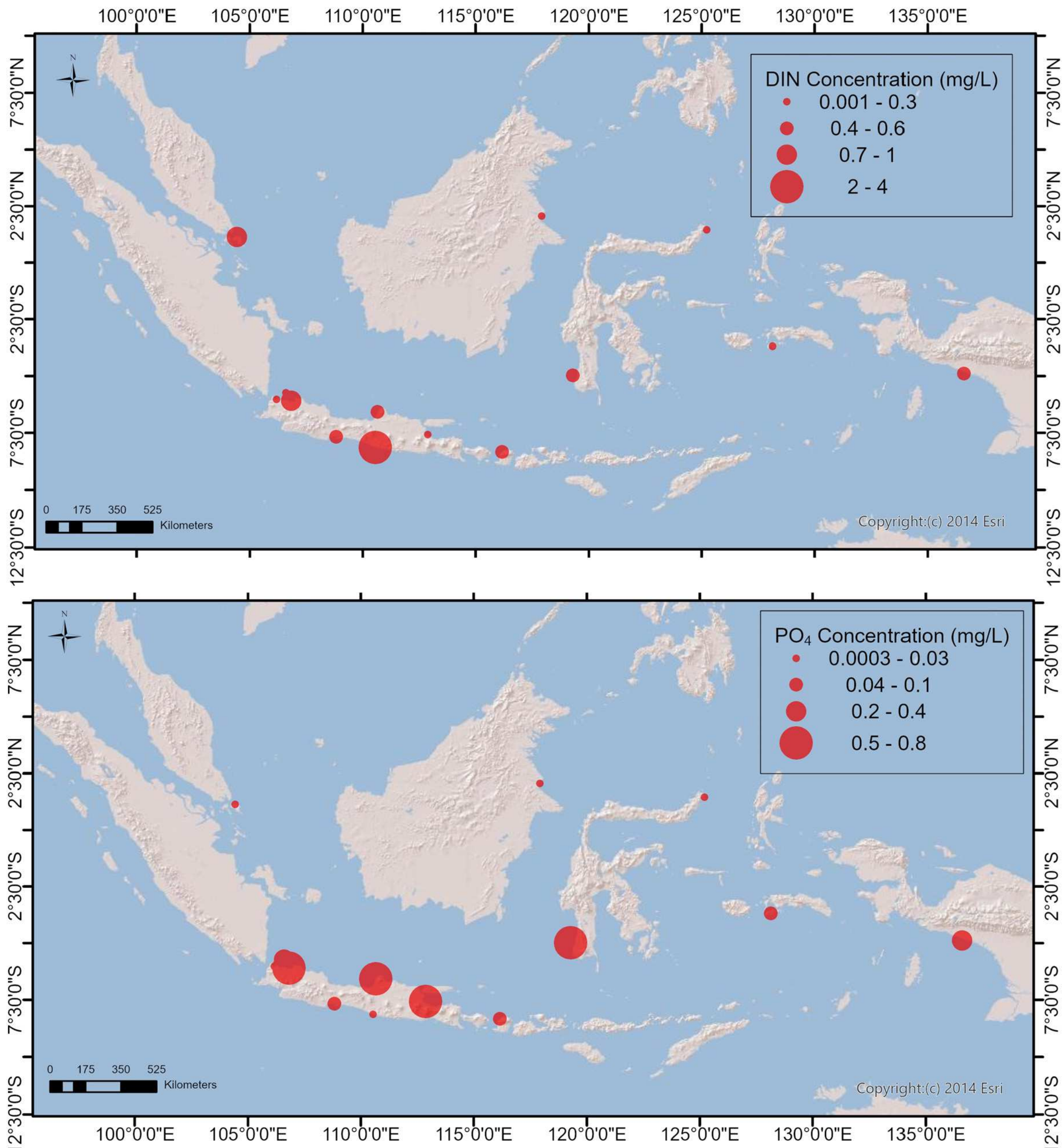

Fig. 3. Spatial distribution of nutrient concentration (DIN and PO_4) in Indonesian coastal water. Sources of this map can be found in Table 1, section "Nutrients".

Southeast Asian coastal megacities such as Bangkok and Manila. On the one hand, Jakarta Bay had higher NO_3 and PO_4 concentration, but lower NH_4 than Bangkok's coastal water (Burnett et al., 2007). On the other hand, all nutrient species were higher in Jakarta Bay than in Manila Bay (Taniguchi et al., 2008).

Hypoxic water mass due to nutrient enrichment was also often observed in Jakarta Bay (Hayami et al., 2020; Ladwig et al., 2016). Frequently occurring eutrophication and HABs were found predominantly at the estuaries, and their occurrence was always associated with increased phytoplankton biomass production (Damar et al., 2019; Damar et al., 2020). Overall, studies related to nutrient transport to coastal areas and eutrophication potential have been conducted in many parts of Indonesia (Sari et al., 2021; Adyasari et al., 2018; Adyasari et al., 2019a; Baohong et al., 2016; Maslukah et al., 2019; van der Wulp et al., 2016b; Alongi et al., 2013; Booij et al., 2001; Muchtar, 2004; RHR and Hamuna, 2019). In parallel, the research on phytoplankton and HABs has increased from 1986 to 2004, with HAB occurrences observed in the islands of Sumatera, Java, Nusa Tenggara, Maluku, and Papua (Sidharta, 2005; Likumahua et al., 2020; Likumahua et al., 2019; Maslukah et al., 2021; Syakti et al., 2019a).

We found that compositional changes of Indonesian coral reefs, mangroves, and seagrass communities were attributed to excessive nutrient loading from land. Studies found that nutrients from agricultural runoff and sewage pollution were discharged via rivers and groundwater to reef communities in areas in northern Java (Edinger et al., 1998), Lombok (Oehler et al., 2019), Spermonde Archipelago (Teichberg et al., 2018; Nasir et al., 2016; Sawall et al., 2011), and Thousand Islands (Baum et al., 2015; Baum et al., 2016a; van der Meij and Hoeksema, 2010; Cleary et al., 2016). Stable isotopic $\delta^{15}N$ analyses of corals from the island of Bali suggest that the intensification of Western-style agricultural practices since 1970 contributes to the degradation of coastal coral reefs in this area (Marion et al., 2005). Seagrass communities were potentially affected by nutrient-rich groundwater discharge from southern Java's karstic region (Oehler

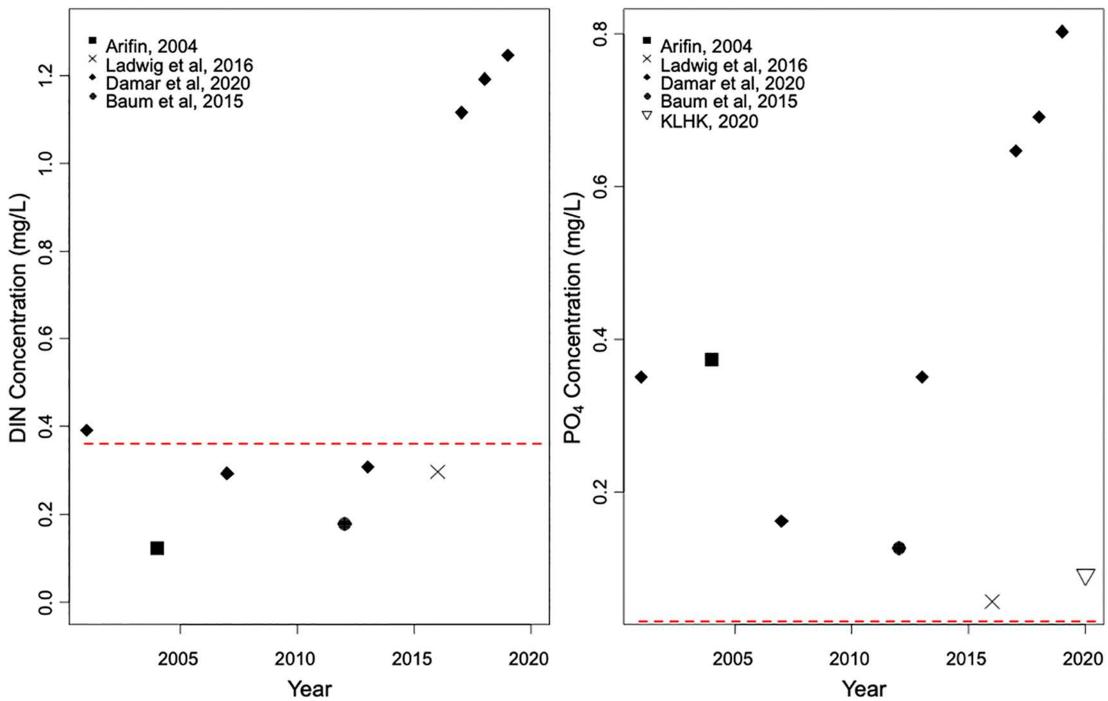

Fig. 4. Twenty-year time series of nutrient concentrations (DIN and PO_4^{3}) showing the current trend in Jakarta Bay (2001–2020). The red dashed line indicates the environmental standard limit (PP 22/2021). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2018). Additionally, Van Katwijk et al. (2011) also observed that seagrass meadows' response to nutrient loading in the East Kalimantan manifests as declining seagrass cover, standing stock, number of species, species composition, and changes in tissue contents. In a pristine environment such as the East Kalimantan, seagrass meadows are potentially used as an early warning to the initial eutrophication process. Nutrient dynamics from anthropogenic activities and deforestation in mangrove-fringed Segara Anakan Lagoon were also extensively studied (Nordhaus et al., 2009; Nordhaus et al., 2019). However, the sustainability of sensitive coastal ecosystems is not always determined by human activities. The nutrient inventory in Segara Anakan Lagoon, for example, was controlled by a complex combination of anthropogenic activities and natural sources such as the residence time of water in the shallow lagoon (Jennerjahn et al., 2009).

3.2. Heavy metals

Heavy metals can be found as naturally occurring elements or byproducts of human activities such as industrial and mining activities. For instance, as a part of the natural elemental cycle, iron is often found in the aquifer or soil of volcanic areas (Syakti et al., 2015). Due to their bioaccumulation capability and toxicity to human and marine biota, the concentration of some heavy metals such as Mercury (Hg), Chromium VI (Cr(VI)), Cadmium (Cd), Copper (Cu), Lead (Pb), Zinc (Zn), Arsenic (As), and Nickel (Ni) are regulated by the national decree PP 22/2021 (Table 2). The biomagnification of heavy metals often occurs in marine biota (e.g., mussels and fish (Riani et al., 2018)), which may cause lung, immune, and neurological damage after human consumption. Of the 28 heavy metals-related field studies reviewed in this paper, 54% of the studies show field concentration exceeding the concentration regulated by PP 22/2021 for seawater and other regulation related to marine sediments (Supplementary Table).

Research related to coastal heavy metal pollution in Indonesia is concentrated in heavy-mining areas in Sulawesi (Lasut et al., 2010; Limbong et al., 2005; Edinger et al., 2008; Edinger, 2012; Edinger et al., 2007; Blackwood and Edinger, 2007; Prisetiahadi and Yanagi, 2008), Papua (RHR and Hamuna, 2019; Brunskill et al., 2004; Alonzo et al., 2016; Tanjung et al., 2019; Morrison and Delaney, 1996), Buru Island (Maluku) (Male et al., 2013; Reichelt-Brushett et al., 2017), and Sumbawa (Nusa Tenggara) (Angel et al., 2013). All of the studies conducted in Sulawesi are focused on Buyat Bay. It involved a coastal water contamination case from gold mining activities, which further involves international criminal and civil lawsuits trial between Indonesia and the U.S, as the mining company's origin (Perlez, 2006). The bay was used as a tailing dumping ground of Hg from gold mining activities; Hg is a byproduct of submarine processing of industrial gold mining tailings and small-scale gold mining, where it is used for amalgamation. The socio-environmental aftermath resulted in massive fish kill and human illnesses such as tumors and rashes experienced by the coastal population. A study from Lasut, Yasuda (Lasut et al., 2010) observed a significant amount of total mercury (THg) and methyl mercury (MeHg) in the hair of the locals. Another study conducted in Buyat Bay found mercury concentration up to 7 mg kg^{-1} in the coastal sediment, which was seven times higher compared to the levels documented by continuous monitoring two years before the activities and 3.5 times higher than the recommended safety level of 2 mg kg^{-1} by the World Health Organizations (WHO) (Limbong et al., 2005). Additionally, in other mining regions such as on the island of Papua, elevated heavy metal concentrations were found in the Ajkwa River, located downstream of the Grasberg mine, the world's single largest known gold reserve (Brunskill et al., 2004; Morrison and Delaney, 1996).

Based on the reviewed studies conducted in the non-mining regions, the highest heavy metal concentrations were of iron (Fe = 103,301 ppm) measured in Segara Anakan Lagoon sediments, attributable to a combination of anthropogenic (wastewater discharge from an oil refinery) and natural sources (volcanic area) (Syakti et al., 2015). Differentiating the contaminant source of heavy metals indeed is complex because many potential pollution sources exist. The problem of distinguishing geogenic from anthropogenic (Booij et al., 2001; Sindern et al., 2016; Wijaya et al., 2019; Williams et al., 2000) or terrestrial from marine sources arises mainly in industrialized cities (Amin et al., 2009a; Scott and Davies, 1997). For example, the coastal city of Dumai (Sumatera) potentially receives allochthonous heavy metals from shipping activities in the Strait of Malacca, one of the busiest international shipping lanes worldwide. Coastal areas of Jakarta are also possibly contaminated with heavy metals because of the oil and gas platforms close to the bay (Scott and Davies, 1997). The type of industries (e.g., textile (Suteja et al., 2020) and electroplating (Takarina et al., 2004)), seasonal variability (Arifin et al., 2004; Najamuddin et al., 2016; Hosono et al., 2011; Siregar et al., 2016), and the interaction with other contaminants (Purwiyanto et al., 2020) also reportedly affect the levels of heavy metal in Indonesian coastal areas.

In comparison to other countries with similar settings, heavy metal concentrations in Jakarta Bay are up to three magnitudes higher than in Bangkok (for sediment, (Rermdumri et al., 2009)) and Manila (for seawater (Velasquez et al., 2002)). A mixed pattern of heavy metal trend is observed in Jakarta Bay coastal water. For example, Cu and Pb have increased 40 and 30 times, respectively, between 1983 and 2014 (Koropitan and Cordova, 2017). In contrast, another study found that for some heavy metal species, such as Pb, their accumulation rates were constant or decreased near Jakarta's coastal industrialized area, due to the stricter environmental regulations which were enforced at the end of the 1990s (Hosono et al., 2011).

A coral reef study in the Jakarta and Thousand Islands reveals that heavy metal concentration in coastal water affected coral composition, diversity, cover, and colony numbers (van der Meij and Hoeksema, 2010; Scott and Davies, 1997; Rachello-Dolmen and Cleary, 2007). Cu and Pb contaminations from the gold mining industry in the Sulawesi were recorded in a hard corals' skeleton in its coastal area (Edinger et al., 2008). In the city of Dumai's mangrove area, stations with enhanced anthropogenic activities resulted in elevated levels of heavy metals and consequently displayed lower abundances, lower species richness, and diversity of mangrove (Amin et al., 2009b). In the less anthropogenically-affected areas, heavy metals were usually found in moderate concentration, such as in the seagrass community of Ambon Bay (Maluku) (Ambo-Rappe, 2014) or Flores Sea (Nusa Tenggara) (Nienhuis, 1986). In this condition, coastal ecosystems may even function as bioindicators or biofilters of heavy metals. A natural accumulation of heavy metals (Cd, Cu, Pb, and Zn) reportedly occurs in certain seagrass species in the Flores Sea and the Java Sea, which makes seagrasses are used as indicator organisms for heavy metal contamination and bioavailability (Nienhuis, 1986; Yona et al., 2020). Analuddin et al. (2017) and Titah and Pratikno (2020) found that the mangroves ecosystem played a significant role in biofiltering heavy metal in Rawa Aopa Watumohai National Park (Sulawesi) and Surabaya (Java), respectively. Therefore, the degradation of the vast mangrove areas by human intervention may increase the heavy metal input in the coastal region.

3.3. Organic pollutants and micropollutants

Organic matter in the environment can be represented as biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), or dissolved organic carbon (DOC). Non-anthropogenic DOC is naturally found particularly in organic-rich coastal areas such as the peatlands, commonly discovered in the island of Sumatera and Kalimantan (Dommain et al., 2011). However, human-induced disasters elevate these levels significantly, acting as pollutants in the coastal water. For example, a peat fire caused by deforestation for palm oil plantations significantly increases fluvial DOC in Sumatera and Kalimantan (Sazawa et al., 2018). A 2006 volcanic mud eruption in East Java, which originated from a blowout of commercial gas wells, increased the riverine TOC export to the ocean about three times compared to the levels prior to the accident (Jennerjahn et al., 2013; Sidik et al., 2016; Kure et al., 2014).

In the last decade, a specific non-biodegradable organic group called Persistent Organic Pollutants (POPs) is gaining attention due to the compounds' toxicity, persistence, and bioaccumulation in the aquatic ecosystem. This group originates from industrial, petrogenic, and agricultural application and includes chemicals such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), diisopropylnaphthalenes (DIPNs), organochlorine insecticides, and dichlorodiphenyltrichloroethane (DDT)—the latter two are commonly used in agricultural countries such as Indonesia (Choi et al., 2017). The majority of these POPs pesticides have been banned (UNEP, 2008), while those not banned are regulated by PP 22/2021. The decree manages the following parameters for the water samples: PAH, phenol, PCB, pesticides, and tributyltin (TBT) (Table 2). 50% of organic pollutant-related field studies reviewed in this paper report exceeding levels of the regulated parameters (Supplementary Table). The rest of the studies report specific parameters or values for coastal or marine sediments not covered by the PP 22/2021 for seawater and other regulation related to marine sediments.

Comprehensive studies assessing POPs, linear alkylbenzene sulfonates (LAS), and other emerging micropollutants were conducted in Jakarta Bay from 2008 to 2014 (van der Wulp et al., 2016b; Williams et al., 2000; Dsikowitzky et al., 2020; Dsikowitzky et al., 2014; Dsikowitzky et al., 2016a; Dsikowitzky et al., 2017; Dsikowitzky et al., 2016b; Dsikowitzky et al., 2018; Dsikowitzky et al., 2016c; Harino et al., 2012). A total of 71 organic contaminants were found in Jakarta's rivers discharging to Jakarta Bay, including micropollutants from municipal wastewater discharge and industrial manufacturing (Dsikowitzky et al., 2020; Dsikowitzky et al., 2014; Dsikowitzky et al., 2016a; Dsikowitzky et al., 2016b; Dsikowitzky et al., 2018). In terms of concentrations and detection frequency, micropollutants such as flame retardant, disinfectant, personal care product ingredients (e.g., sunscreen, insect repellant), stimulants (e.g., caffeine and nicotine), and pain reliever (e.g., ibuprofen and mefenamic acid) were found to be the most important source-specific compounds from municipal sources, as these compounds occurred in exceptionally high concentrations as compared to studies of other river and coastal systems in Asia, United States, and Europe (Dsikowitzky et al., 2016b). DDT, which originates from pesticides and is considered a legacy from agricultural activities in the 1980s, is now banned; thus, their current detection in Indonesian water and biota significantly reflects their persistency over more than three decades (Dsikowitzky et al., 2016a).

The composition of organic pollutants also gives insights into the level of industrialization in a specific region: For example, Koike et al. (2012) reports in a comparison study implemented in Jakarta Bay (Indonesia) and Tokyo Bay (Japan) that even though both cities are considered megacities, Tokyo Bay was the more industrialized (with higher PAHs and PCBs), while Jakarta Bay was characterized as a less industrialized city but with a high contribution of municipal sewage (higher LAS concentration). Similarly, another study found that LAS concentrations in Jakarta Bay sediments were the highest so far detected in any Asian countries (Dsikowitzky et al., 2016c). PAH concentration shows alarming trend in Jakarta Bay, as its concentration increased 30 times between studies conducted in 2000 (up to 50 μg kg^{-1} (Williams et al., 2000)) and 2012 (up to 1500 μg kg^{-1} (Koike et al., 2012)). Other studies outside Jakarta also associate high organic pollutants with specific human activities, such as shipping activities (Morrison and Delaney, 1996; Sudaryanto et al., 2005; Evans et al., 1995), cities and industrial centers (Booij et al., 2001; Ilyas et al., 2011; Bouhroum et al., 2019; Noor et al., 1987), oil and gas industry (Liebezeit and Wöstmann, 2009), or aquaculture ponds (Hidayati et al., 2021; Alongi et al., 2009).

A combination of PAHs and LAS has reportedly caused a metabolic depression in the Thousand Islands' coral ecosystem (Baum et al., 2016b). The chemical compound Perylene, a proxy of petrogenic contamination, accounted for about 60% of the total PAH concentrations in the coral reef-dominated the Berau Delta (Kalimantan) (Booij et al., 2012). Another ecosystem threatened by petrogenic contamination is the mangrove-fringed Segara Anakan Lagoon (Syakti et al., 2013). It was found that the 50 types of PAHs in water, sediments, and benthic organisms detected in the Segara Anakan Lagoon presumably came from the nearby city of Cilacap (Dsikowitzky et al., 2011). In recent petroleum accident cases in Kalimantan and Java, oil spills from a broken underwater pipeline resulted in coating of mangrove trees' roots with oil, and subsequently reducing their ability to exchange gases (Ghozali et al., 2017).

3.4. Plastic debris and microplastics

Plastic debris, whose concentration increases significantly in the last decade due to the higher usage of single-use plastic, can be categorized into three categories: microplastics, mesoplastics, and macroplastics (Lestari and Trihadiningrum, 2019). Compared to other pollutants, plastic debris can be categorized as a "new" type of pollutant as it became a subject of research in the last decades, and thus, currently, there are no established environmental regulations for plastics in Indonesia. While other chemical or biological matters reviewed in this paper can also be found naturally in the natural systems, plastic debris is a pure anthropogenic activities byproduct. The most widely used plastic types by far are polymers such as polystyrene (PS), polypropylene (PP), and polyethylene (PE), which are usually used in making plastic films, materials for packaging, automotive parts, pipes, and houseware (Worm et al., 2017). Microplastics may act differently from more oversized items due to their increased surface area, their ability to be transferred across tissue or cellular boundaries, or their interactions with other chemicals in the environment (Cole et al., 2011).

Purba et al. (2019) and Lestari and Trihadiningrum (2019) have reviewed the current status of plastic debris research in Indonesia, including some local studies that are not captured by our methodology. They found that most of the studies were conducted in western Indonesia and focused on macro debris across the beach. Of the ten inspected locations, the highest microplastics abundance of 37,440–38,790 particles/kg dry weight sediment was found in Jakarta Bay (Lestari and Trihadiningrum, 2019). The most up-to-date plastic debris-related study observed an increase in plastic-made personal protection equipment (PPE) waste in Jakarta Bay after the COVID-19 pandemic (Cordova et al., 2020a). In comparison to other pollutants, plastic-related research is still predominantly conducted in the industrialized Javanese cities, i.e., Jakarta (Cordova et al., 2020b; Willoughby et al., 1997; Uneputty and Evans, 1997a; Cordova and Nurhati, 2019), Surabaya (Cordova et al., 2019; Firdaus et al., 2020; Kurniawan and Imron, 2019a; Kurniawan and Imron, 2019b; Lestari et al., 2020), Semarang (Khoironi et al., 2020), Banten (Falahudin et al., 2020), and Cilacap (Bouhroum et al., 2019; Syakti et al., 2017). Only five studies are implemented outside Java (i.e., Bintan (Sumatera) (Syakti et al., 2018; Syakti et al., 2019b), Palembang (Sumatera) (Purwiyanto et al., 2020), Bali (Nusa Tenggara) (Suteja et al., 2021), and Ambon (Maluku) (Uneputty and Evans, 1997b)). The PS, PE, and PP with sizes between 300 and 1000 μm were the most commonly found in the study sites, suggesting the state of microplastic particles that have not deteriorated for a long time (Cordova et al., 2019). Microplastics were also discovered in the intestines of fish from Jakarta Bay (Cordova et al., 2020b; Sembiring et al., 2020) and mussels from Semarang Bay (Khoironi et al., 2020). The fish often consume microplastics with sizes ranging from 300 to 500 μm because of difficulty distinguishing between their food and the microplastics (Cordova et al., 2020b). Overall, microplastic study results from some Indonesian sites show a higher amount compared to another site in the region. For example, microplastics found in Jakarta (9 n m^{-3} (Cordova et al., 2020b)) and Surabaya (43 n m^{-3} (Lestari et al., 2020)) estuaries, the two biggest industrial cities in Indonesia, are higher than microplastics in the Pearl River estuary (2.3 n m^{-3} (Lam et al., 2020)), one of the most populated catchment areas in China.

We only found three studies associating a specific ecosystem with plastic debris in Indonesia. A study conducted in northern Java revealed that prolonged suffocation by plastic caused rapid pneumatophore growth and potential leaf loss of mangroves (van Bijsterveldt et al., 2021). Another study in the Jakarta mangrove ecosystem showed that most plastic debris originates from textile and fishing gears (Cordova et al., 2021). Furthermore, while macro beach litter with a size more than 5 cm in length was found in Thousand Islands, there was no correlation with the native coral communities (Willoughby et al., 1997). The negative impacts of plastic debris on seagrass/coral reefs have been studied in other parts of the world (e.g., (Balestri et al., 2017; Lamb et al., 2018)); however, similar studies have not been done in Indonesia and but should be recommended in the future, considering these preliminary findings. Additionally, as Jakarta had effectively banned single-use plastic bags in supermarkets in 2020 (Reuters, 2020), it is interesting to examine how the future coastal and marine plastic debris dynamics respond to this ban.

3.5. Other pollutants

3.5.1. Fecal indicator and pathogenic bacteria

A pathogen is defined as a parasite organism causing the disease to its host, whereas an enteric pathogen is defined as any microorganism that can cause enteric disease (Kolling et al., 2012). Due to abundant species of pathogen, fecal indicator organisms such as total coliform, fecal coliform, and *E. coli* are commonly used in representing the presence of the microorganism (Motlagh and Yang, 2019). Based on a study of coliform pollution modeling on a global scale, it was found that southwest and eastern Asia rivers have severe pathogenic pollution due to inadequate access to wastewater treatment infrastructure (UNEP A, 2016). The national decree PP 22/2021 regulates biological contamination in fecal coliform, total coliform, and pathogenic bacteria (Table 2). In comparison to other chemical pollutants in the database, we found that biological-related pollution studies are still limited in the island of Java (Adyasari et al., 2019b) and Sulawesi (Kegler et al., 2017). In Sulawesi, coliform related to human sewage was identified in the coral reef ecosystem of the Spermonde Archipelago. This was found to cause impairment of coral larvae, which potentially results in lower coral coverage and change of dominant reef communities from corals to algae or soft corals (Kegler et al., 2017).

3.5.2. Radionuclides

The distributions and effects of both naturally occurring (radon, ^{222}Rn) and man-made radioisotopes (cesium, ^{137}Cs) were studied. The national decree regulates any radionuclide with a maximum limit of 4 Bq L^{-1} or equivalent with 4000 Bq m^{-3}. Based on this standard, none of the detected radioactivity levels in the reviewed studies violate the environmental standard limit. For example, ^{222}Rn concentrations up to 800 Bq m^{-3} were found in the northern Java's estuary and coastal waters (Adyasari et al., 2018; Adyasari et al., 2019a), while the maximum ^{222}Rn concentration of 1090 Bq m^{-3} was observed in submarine springs in Lombok (Nusa Tenggara) (Oehler et al., 2019). However, these studies only employed ^{222}Rn as groundwater tracer and did not investigate the environmental or health impact of ^{222}Rn on local populations. The anthropogenic radionuclide cesium (as ^{137}Cs) is produced by industrial activities with an average concentration of 0.2 Bq m^{-3} in Demak, a medium-sized industrial city in Java (Muslim et al., 2017). Interestingly, a two-year study across the archipelago points to radionuclide detection in eastern Indonesia (ranged 0.1–0.7 Bq m^{-3}) as a result of the Fukushima nuclear accident in Japan (Suseno and Prihatiningsih, 2014). High ^{137}Cs levels were also found in marine biota, sediment, and coastal water, particularly in Sulawesi and Nusa Tenggara islands (Suseno and Wahono, 2018). The global environmental impact from the Fukushima accident was a result of the Indonesian Throughflow Current, which brings warm water from the Pacific Ocean (including Japanese coastal waters) to the Indian Ocean via Indonesia (Suseno et al., 2017).

4. Open questions and future research directions

4.1. Impact of climate change

Climate change is one of the main driving forces that may alter water quality and the function of the coastal ecosystems and marine waters worldwide (Rabalais et al., 2009). Coral reefs, in particular, are susceptible to climate change effects, as human activities, rising seawater temperature, and ocean acidification are primary stressors to coral disease and mortality (Hughes et al., 2003). A numerical modeling study for Java Island demonstrates that climate change scenarios result in an increase of surface runoff, a reduction in river base flow, and alteration of groundwater recharge and distribution (Ridwansyah et al., 2020). In these potential future scenarios, river- and groundwater-derived pollutant fluxes will also significantly change and subsequently alter the coastal water quality status. Seawater intrusion, particularly, reportedly influences the biogeochemical cycle in the coastal sediments. For instance, Seitzinger et al. (1991) discovered that increased salt content in the organic-rich coastal layer might lower the fraction of the NH_4 produced in sediments that are nitrified and subsequently denitrified, resulting in an increase of terrestrial NH_4 to the ocean (Breitburg, 2002). Such an investigation is particularly compelling considering that large areas of the islands of Sumatera and Kalimantan coastline consist of peatlands, i.e., sediments with significantly high organic matter (Dommain et al., 2011). Increased NH_4 in the coastal water is known to cause anoxic or hypoxic events that may lead to fish kills worldwide (Breitburg, 2002; Montiel et al., 2019).

Additionally, changes in physical drivers associated with climate change, such as seawater mixing, circulation, and temperature, are known to affect coastal primary production (Holt et al., 2016). The increased temperature in tropical areas imposes even higher stress on cells already growing at a high-temperature limit. Compared to polar and temperate systems, where an increase in seawater temperature seems to counteract the impact of solar UV radiation, elevated temperatures reinforce the UV radiation impact in tropical waters (Haeder et al., 2014). Therefore, the alteration of primary productivity pattern, in addition to increased terrestrial nutrient runoff, potentially results in the higher occurrence of eutrophication and algal blooms in the tropics. Nevertheless, climate change-related studies investigating these effects on the Indonesian coastal water and ecology are still very limited even though 90,000-km of total natural Indonesian coastline has decreased by 6000 km from 1998 to 2018, while the artificial coastline increased by 6800 km due to population growth (Sui et al., 2020). This result demonstrates that while climate change variables are evidently significant drivers to coastal dynamics, anthropogenic impacts still are considered the major ecological issue in Indonesia. Therefore, future studies on the impact of climate change on Indonesian coastal areas are required and must be highly prioritized. Specifically, since climate change is a gradual process, long-term monitoring is suggested to be incorporated into future research plans.

4.2. Newly developed coastal cities—new coastal pollution hotspot?

As Indonesia is transitioning towards an industrialized nation (OECD, 2018), it is expected that land-use modifications will be even more prevalent in the near future. In the last decades, increasing economy and development has transformed formerly medium-sized coastal cities such as Surabaya (Java), Medan (Sumatera), and Makassar (Sulawesi) to metropolitan status (population $>$ 1 million) (World Bank, 2010). As Indonesia's elevated urbanization level is not always accompanied by the development of environmental or sanitation infrastructures (Asian Development Bank, 2016), newly developed coastal cities potentially become coastal pollution hotspots. The urbanization trend reveals higher population growths in Kalimantan, Nusa Tenggara, and Papua than Java (Sembiring et al., 2020), which prompts to focus coastal environmental studies in these areas.

More research conducted in these parts of Indonesia may also counterbalance the current research gap or discrepancy between studies implemented in Java and non-Java islands. This spatial bias is associated with the logistical problem and the location of research facilities, which are mainly located in Java as Indonesia's most developed island. For example, while eastern Indonesia has environmentally significant local attributes (e.g., Coral Triangle) and pressing ecological problems (e.g., oil and mining areas), its remote location, the lack of scientific infrastructures, and limited transportation options often hinder field research in this region. However, the fast economic development in some eastern Indonesian cities, such as Makassar, could have a positive effect by expanding much-needed scientific infrastructure in the eastern region for the near future.

Nevertheless, we foresee the relocation of the current capital Jakarta to Kalimantan and its future development and urbanization as detrimental for the ecology of the island of Kalimantan. Currently, the southeastern part of Kalimantan, where the city is planned to be built, is dominated by dense rainforest and extensive national parks that are vital habitats for orangutans. The impacts of anthropogenic activities on the coastal ecosystem have been detected in the Mahakam Delta, which is the Indonesian largest delta located in southeast Kalimantan (Arifanti et al., 2019). The construction of the new capital will include deforestation of the rainforest, followed by urbanization, which undeniably would alter the current coastal ecosystems. The data presented here clearly suggests the need for further research on non-Java islands, which have received comparatively little scientific attention to date despite being a hotspot of coastal ecosystems (Fig. 1).

4.3. Terrestrial vs. marine anthropogenic factors

Terrestrial-derived pollutants have been identified as the most significant coastal pollutions worldwide, which is also confirmed in Indonesia by the reviewed studies for this work. However, depending on the geography and mixing patterns in specific locations, marine-based pollutants can also be a significant source of coastal water pollution. This condition is particularly applied in coastal areas close to the big commercial ports (Jahan and Strezov, 2017) or offshore oil platforms (Holdway, 2002). Because of its archipelagic nature, the Indonesian coastal cities host some of the busiest trading ports in Asia or even globally (Staff, 2020). Additionally, Indonesia also has vast offshore oil reserves (Bee, 1980). Commercial oil platforms are scattered mainly in Sumatera, Kalimantan, and Papua, which potentially produces oil pollution that could be transported to nearshore areas. Based on this review, only four studies focus on marine-based anthropogenic pollutants in Indonesian coastal areas. Of them, three studies related to an oil spill and oil platform-sourced pollutants (Scott and Davies, 1997; Liebezeit and Wöstmann, 2009; Ghozali et al., 2017), and one to port and harbor point source coastal pollutant (Amin et al., 2009a). In summary, the topic of marine-based anthropogenic pollutants in Indonesia is still largely unknown, and it requires more investigation in the future.

4.4. Legacy and emerging pollutants

A legacy pollutant is described as a pollutant originating from long-term industrial or agricultural operations, and from which active release into the environment has ceased. This group often includes POPs (from industries and pesticides) and nutrients (from fertilizers). Studies on legacy pollutants often focus on two research subjects, i.e., marine organisms and groundwater. POPs bioaccumulation in Indonesian marine biota is well-studied (Isobe et al., 2007; Monirith et al., 2003; Nakata et al., 2012; Ramu et al., 2007; Sudaryanto et al., 2002). However, research identifying the role of legacy pollutants in the aquifer systems and coastal areas is not yet available. The age of groundwater in the local aquifer spans from days to years or even decades, and as a result, it could record contamination events from the past. For example, an agricultural boom in Indonesia took place in the 1980–1990s when the Indonesian Government heavily subsidized fertilizers and pesticides application to increase crop productivity. These practices were ceased in the early 2000s when Indonesia became a Stockholm Convention party (Hedley and Tabor, 1989; Mariyono, 2008); however, some pesticides such as DDT are still detected in the coastal areas as late as 2013 (Dsikowitzky et al., 2016a). Therefore, based on the current understanding of groundwater ages, groundwater polluted decades ago is now potentially discharging into the rivers, estuaries, or coastal waters. Thus, interdisciplinary studies combining multifaceted approaches (e.g., groundwater dating, recharge and discharge areas, tracers) are much needed in the future to fill this research gap. Additionally, studies related to emerging pollutants, which refer to replacement substances for the legacy chemicals, have only recently been conducted in Indonesia (see Chapter 3.3). Currently, emerging pollutants are only studied in Javanese cities and but must be potentially expanded outside Java, particularly in tourism hotspots such as Bali and other Nusa Tenggara islands.

4.5. State-of-the-art microbial-related research

With the changing coastline and expanding urbanization, it is projected that biogeochemical processes or microbial-related environmental status will also be altered. We pointed that, based on current understand and global trends, the alteration of biogeochemical cycles, mediated by specific microbial communities, is highly possible under climate change conditions in the future. However, microbial-focused studies on coastal elemental cycling from Indonesia are still very scarce. Currently, there is only a study from Adyasari et al. (2019b) that identifies microbial communities using 16S rRNA sequencing and their potential in regulating the nitrogen cycle in Java. Additionally, there is a significant gap in understanding pathogen contamination in the coastal area to be filled by future research. While some studies associate municipal areas or livestock as the sources of coastal biological contamination, more studies need to be conducted in areas with extensive aquacultures to identify their role as point source pollution. The Asian Development Bank (2016) reports that aquaculture activities are one of the most significant point sources of pollution to the Indonesian coastal areas due to its relative contribution to the total land-use area. Therefore, future studies should include the aquacultural farming aspects to delineate its adverse contribution to the coastal water quality.

The current knowledge of biological processes and pollution in Indonesia could be improved by incorporating more state-of-the-art molecular approaches in coastal studies. Most local biological pollution studies used microbial indicators such as *E. coli* and total coliform analyses, resulting in Most Probable Numbers (MPN) or CFU (coliform per unit) units. While these traditional enumeration methods have some advantages of being low-priced and can be quickly implemented, these methods do not precisely identify pathogenic bacteria. These limitations could be overcome with molecular methods such as Polymerase Chain Reaction (PCR) or the so-called omic approaches (i.e., related to microbial genomes, proteins, metabolites, or transcriptomes). These approaches provide higher sensitivity and reliability in determining the metabolic processes, microbial identification, contamination levels, or/and the occurrence of waterborne pathogenic bacteria in the study sites.

Interdisciplinary studies, such as combined microbiological and hydrogeological aspects, are also lacking in Indonesia. In other Southeast Asia countries, such as Vietnam and Singapore, studies relating bacterial assemblages with organic micropollutants (Hoa et al., 2011) and microplastics (Curren and Leong, 2019) have been conducted. Considering organic pollutants and microplastics studies are relatively abundant (Fig. 2), correlating them to the biological processes may provide new insights, especially concerning the biodegradation potential of these contaminants in coastal environment.

4.6. The future of Indonesian coastal ecosystems

This paper reviews 28 studies related to the anthropogenic impact on coral reef, mangrove, and seagrass ecosystems. Between the three ecosystems, the coral reefs appear to be the most sensitive to anthropogenic disturbance. A 2018 study by the Indonesian Institute of Sciences (LIPI) states that the coral reefs statuses on 1067 sites throughout Indonesia are dire: 366 sites (34%) are in the poor category, 386 sites (36%) are in the category of high concern, 245 sites (23%) in the category of lower concern and 70 sites (6%) in the excellent category (LIPI, 2018a). On the other hand, the status of seagrass in Indonesia was categorized as the moderate category according to a LIPI study measuring the percentage of seagrass coverage in 110 sites in 2018 (LIPI, 2018b). A similar trend is also observed in the mangrove ecosystem: of the 3.31 million ha mangrove area in Indonesia, 2.67 million ha (80%) was still categorized as good condition, while 0.64 million ha was in a critical condition by 2019 (Ministry of Environment and Forestry, 2020). Still, degraded mangroves affect their ability to accumulate and store carbon: lower carbon stock was reported in the degraded area (167 Mg C Ha^{-1}) than in the undegraded area (438 Mg C Ha^{-1}) (Kusumaningtyas et al., 2019).

Various shareholders have executed the rehabilitation of these ecosystems. For instance, the Indonesian Government has committed to rehabilitating approximately 600,000 ha of the degraded mangrove area in the nine most affected provinces (Anugrah, 2021). To rehabilitate Indonesian coral ecosystems, a Coral Reef Rehabilitation and Management Program (COREMAP) started in 1998 and included institutional strengthening, public awareness, community-based and sustainable management of coral reefs (LIPI, 2011). In many cases, the rehabilitation worked. A study in Bali found that mangroves in abandoned aquaculture ponds had recuperated some of their functions after ten years of rehabilitation (Sidik et al., 2019). Another study in Jakarta Bay's reef system shows that recovery of offshore coral cover was observed between 1995 and 2005 (Cleary et al., 2014). While further degradation is predicted due to higher human activities in the coastal zone, rehabilitation of some of these ecosystems could also be expected if strictly adhering to the science-based recommendations. Therefore, future studies should also attempt to assess rehabilitation success from ecosystems formerly affected by human activities.

5. Summary and outlooks

In this paper, coastal ecosystem and water quality issues in Indonesia were compiled, described, and discussed. Based on the available studies published between 1986 and 2021, we found that the most pressing issue is related to nutrient pollution, as 82% of studies we reviewed show nutrient concentrations exceeding the standard limits, compared to heavy metals (54%) or organic pollutants (50%). The results of these studies are consistent with the Asian Development Bank findings that coastal water quality is relatively poor and requires immediate attention (Asian Development Bank, 2016). Studies indicate that the excess of nutrients to coastal ecosystems is correlated to ecological events such as hypoxia, eutrophication, or HABs. Additionally, we found that high nutrient loads have resulted in declining habitat cover, number of species, composition, and diversity of the ecosystems. Based on the reviewed papers, both point (e.g., municipal wastewater, oil and mining, and industrial activities) and non-point sources (e.g., agriculture, urbanization, land use development, and groundwater discharge) contribute to the excessive pollutant fluxes and levels in the Indonesian coastal zone (see also Graphical Abstract).

While numerous studies covering different solutes (nutrients, heavy metals, organic pollutants, plastic debris, and microplastics) have been conducted in Indonesia, some research focuses still need to be studied in detail to better estimate the contribution and influence of various solutes in Indonesian coastal water. In addition to the recommended future research directions for understanding the pollutants and climate change impacts on Indonesian's ecosystems (chapter "Open questions and future directions"), it is also suggested that the current environmental standard to be updated. Specifically, there is a need for regulations for plastic debris/microplastics, as well as heavy metals and organic pollutants in sediments, as they are usually found in higher concentration in sediments than water column.

Following current trends in big data storing and archiving worldwide, we recommend optimizing the environmental database, an open public access database provided by the Ministry of Environment and

Forestry (https://dataalam.menlhk.go.id/). This database has the potential to facilitate and expedite future ecological studies by providing quick access to previously done research. Currently, this database has not been well explored and analyzed for more advanced study. Additionally, data related to coastal ecosystems can be found at the National Data Center for Coastal Ecosystem (http://gis.oseanografi.lipi.go.id/, provided by the Indonesian Institute of Science (LIPI)) or Center for Remote Sensing Utilization (https://spbn.pusfatja.lapan.go.id/maps/624, provided by National Institute of Aeronautics and Space (LAPAN)). These websites provide Geographic Information System (GIS) information on water quality, ecosystem status, coral reef indices, data node, and distribution map of coral, seagrass, and mangrove. The websites also document the most current ecosystem status. However, the information seems to be not updated regularly, and there are no links between the water quality database of the Ministry of Environment and Forestry and LIPI. As research progresses, it is strongly recommended that both local and international scientists conducting research in Indonesia archive their findings in these databases. This will optimize the research by helping to focus on the pressing issues. The database will allow easy identification of spatial and temporal distribution of pollutants, and it will also facilitate modeling work which is very scarce in Indonesia but urgently needed in the face of future threats of climate change and sea-level rise.

Overall, we suggest that the processes and studies described in this review may be important in tropical coastal ecosystems worldwide, particularly in developing nations where environmental managements may be limited by legislation or socio-economic concerns. Compiling and analyzing multi-decadal data may reveal the major players in coastal water quality issues and may facilitate the identification of coastal habitats that are most vulnerable to contaminant loading from the watershed. However, studies also show that local or regional influences like natural (e.g., coastal morphology and hydrogeology) and anthropogenic (e.g., population size and land use) factors must be taken into account when comparing different systems.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112689.

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