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Abandoned, lost, or otherwise discarded fishing gear in coastal fisheries: A case study in the Baltic Sea coastal waters of Latvia

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ABSTRACT

Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is considered a problem of global concern which can cause considerable negative environmental and socioeconomic consequences. Due to use of slowly degrading plastic materials in fishing gear construction, ALDFG can remain in marine environment for decades. Enclosed marine environments are particularly vulnerable for all types of pollution and anthropogenic effects, including pollution resulting from ALDFG. However, the extent of this problem is often not estimated. We estimated the level of ALDFG accumulated in a semi-enclosed coastal marine environment in the Gulf of Riga and along coastal areas of the Baltic Sea which are particularly susceptible to different types of marine pollution, including ALDFG. We based our results on a pragmatic approach of using existing ALDFG estimates. The results showed a potentially considerable amount of derelict fishing gear accumulated over the last decade, specifically gillnets and entangling nets and trap gear (2762 netting sheets (CI: 969–4976) and 1379 lost traps (CI: 473–2337)). Therefore, this study highlights the need for the fisheries management to implement adequate ALDFG monitoring mechanisms and subsequent clean-up operations to limit continuous pollution and ghost fishing.

1. Introduction

Abandoned, lost, or otherwise discarded fishing gear (ALDFG), often referred to as “derelict fishing gear” [1], causes global concerns for fisheries sustainability. This relates to its subsequent negative effects on both target and non-target species, marine and coastal habitats and humans [2].

Currently fishing gears are fully or in large parts made of non-biodegradable plastic materials which are preferred by fishers due to being inexpensive and durable materials that provide optimal efficiency of the fishing gear [3]. However, this durability and poor degradability [4,5] can cause multiple negative effects on the marine environment in case of gear loss. First, such gear can remain in the marine environment for decades and potentially cause risk for continuous capture of marine animals (so-called “ghost fishing”) by ALDFG for prolonged time [6]. Ghost fishing is defined as the mortality of aquatic animals that takes place after all control of fishing gear is lost [7]. Secondly, even after the material eventually breaks down into smaller parts and the associated ghost fishing stops, it remains in the environment in form of larger and smaller plastic particles (including micro- and nano-plastics) that further can cause damage by entering the marine food web [8] and cause other associated negative effects on the benthic marine environment [9]. ALDFG can also damage benthic marine habitats [10], result as beach litter and pose entanglement risk for birds and mammals when washed ashore [11]. It can potentially create further risks for entanglement with other fishing gear and vessel propulsion systems, causing potential hazards to navigation and safety at sea [2,7,12]. ALDFG represents a considerable amount of the total marine debris [13]. However, this amount and potential impacts on the ecosystem, especially in enclosed and semi-enclosed areas with limited water currents and exchange, is often unknown. The amount of ALDFG can differ between specific areas due to differences in environmental and geographical conditions, and also the intensity of human activities, including fisheries [1]. The Gulf of Riga and the western coastal areas of Latvia are part of the Baltic Sea which is a semi-enclosed sea in northern Europe with nine coastal countries (Denmark, Latvia, Lithuania, Estonia, Finland, Germany, Poland, Sweden and Russia) (Fig. 1a).

It is largely a shallow, brackish-water body with large freshwater input coming from rivers and inputs of more saline water from the North Sea. It is often referred to as a large semi-enclosed estuary [14–16]. The

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salinity gradients affect the species composition of this region. Depending on the area, it comprises of marine, freshwater and diadromous species [15]. Such semi-enclosed sea with densely populated shores and maritime and fishing activities combined with limited water exchange is considered a highly vulnerable environment to various types of marine pollution [16]. However, research on marine plastic pollution in the region is to date limited [16,17]. A previous study carried out in southern part of the Baltic Sea showed that plastic debris constitute the main part of overall benthic marine litter in the region and identifiable fishing gears were found in 22% of cases, constituting second largest, in terms of abundance, category of benthic marine debris [16]. The ecosystem in the coastal areas of Latvia and the Gulf of Riga (Fig. 1b) should be considered as an autonomously functioning part of the Baltic due to being an enclosed marine area [18]. Thus, it is of particular interest regarding anthropogenic pollution, including ALDFG. The Gulf of Riga surface area is 19,000 km^2 and the maximum depth reaches 67 m [19]. Most of the pollution loads in the Gulf of Riga generally can be attributed to human activities [19].

Fishing is known to impact heavily on the resources and state of the Baltic Sea [15]. The coastal areas within the Baltic Sea where national fleets were legally allowed to operate have changed over time [15]; however, coastal fisheries have been a significant commercial activity in the area historically. There is no available statistics over the years about the fishing gear losses in the coastal fisheries of this region. Also globally, until the mid-1990s, the research on ghost fishing by different fishing gear types was generally scarce [7]. In recent years, more research on derelict fishing gear and loss rates is being conducted as the topic gains more attention [7,2,20–23]. However, the status in many regions and fisheries remains unresearched.

The efforts for recovering ALDFG in Latvia so far have been limited to few local projects [24]. However, the results of such clean-up operations have demonstrated the presence of ALDFG in the coastal areas in both Gulf of Riga and along the coast of Latvia in the Baltic Sea as fractions of, for example, trawl nets and gillnets, corresponding to the fishing gear that has been used in the coastal fisheries in the area and has been accumulated for decades [24]. Specifically, records from previous clean-up operation in Gulf of Riga showed that lost trawl nets have a potential to remain in this marine environment and continue ghost fishing for decades. The recovered nets were estimated to be lost for approximately 40 years based on the gear construction. During the recovering operation by diving, both dead and live fish (mostly round goby (*Neogobius melanostomus*) but also other, including non-identifiable organisms) were observed entangled in the nets (Fig. 2).

Even though the presence of ALDFG is a well-known challenge, including for fisheries management [13,25], there remains a considerable uncertainty over the amount, type and impacts of gear loss in the commercial coastal fisheries in the study area. Thus, the level and risk of associated plastic pollution resulting from ALDFG is complicated to estimate. Environments consisting of semi-enclosed marine areas are particularly susceptible to different types of marine pollution. Therefore, the purpose of this study is to summarize the potential gear loss rates in the coastal areas of Latvia, including the Gulf of Riga and western coast of Latvia in the Baltic Sea. Specifically, the objective of this study is to:

(1) review the available data on the commercial coastal fishing fleet in the area,

(2) review the potential corresponding fishing gear loss rates based on previous estimates available in the scientific literature, and

(3) based on this information, estimate potential levels of contribution to ALDFG by the most common fishing gear types used in this area.

While the focus of this study is on particular regional area, the ideas presented, particularly regarding the pragmatic approach of estimating gear loss rates in absence of recording of ALDFG over the years, are equally relevant to other regional areas and fisheries.

2. Materials and methods

The aim of gathering the information on fishing fleet development during the last decades and fishing gear types used is to facilitate further estimation of the fishing effort and associated fishing gear losses. In this study, we considered the fishing gear use statistics in commercial coastal fisheries for period starting from 2010 as the basis for this review due to available information about the fishery, considering number of operating fishing boats and fishing gear used. Further, potential gear loss rates were estimated based on previous studies showing the percentage of gear lost per year in each considered fishing gear type. The information for this study was acquired and processed as described below.

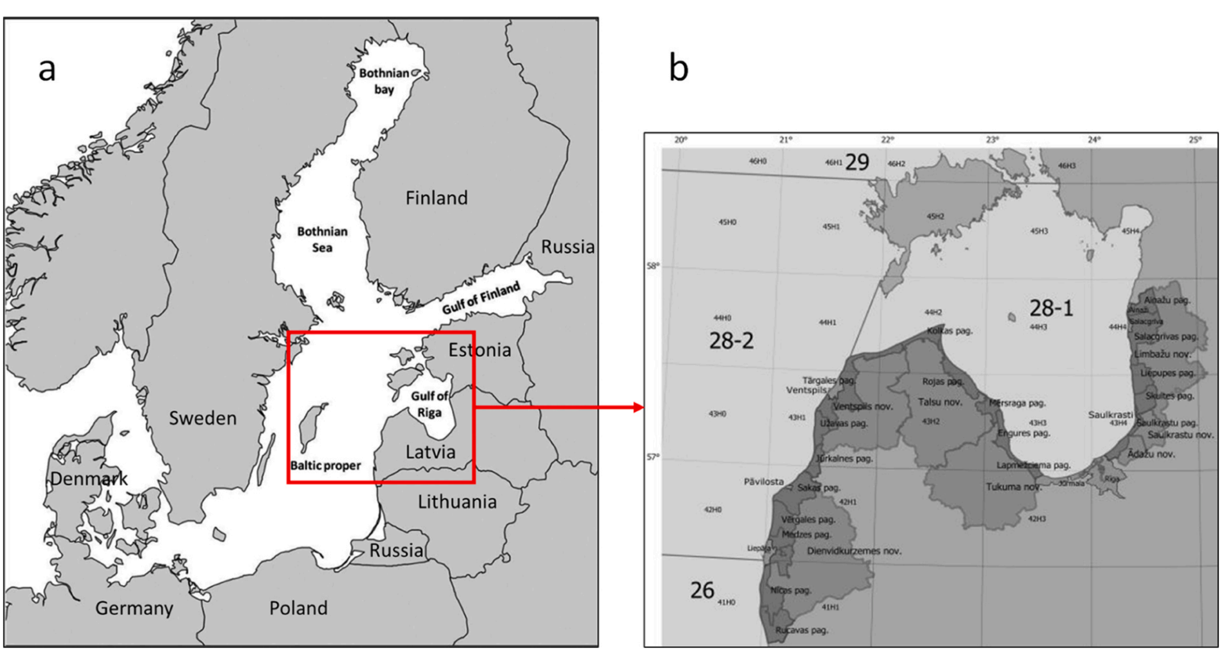

Fig. 1. Map of the Baltic Sea: (a) map of the whole Baltic Sea region and (b) coastal marine areas considered in this study (within ICES areas 28-1 and 28-2).

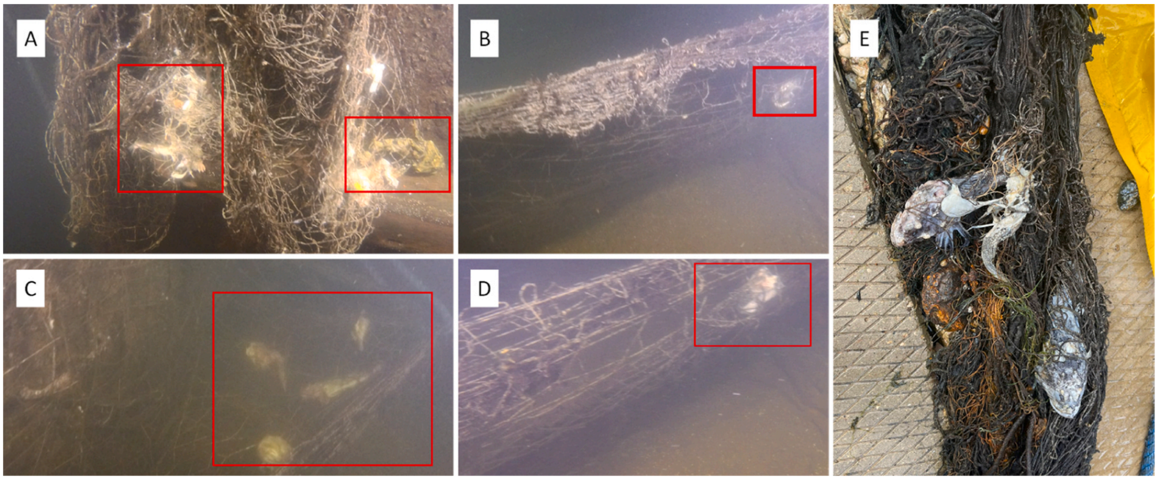

Fig. 2. Example of abandoned, lost or otherwise discarded fishing gear, Gulf of Riga along the coast of Engure, Latvia. (A–D) Underwater images of the derelict net at sea showing ghost fishing (marked in red) (E) Image of part of the retrieved ghost fishing net on land. Images: Riga Technical University.

2.1. Acquiring information for estimation of the fishing effort and fishing gear used in coastal fisheries in the region

All available information and data for the coastal fishery in the Gulf of Riga and coastal waters of Latvian territory (Fig. 1), were retrieved from different sources. The historical information about the fleet and common fishing gear types of the early 1990s after the collapse of the Soviet Union (1991) can be obtained from reports. Specifically, there are no available quantitative historical information on vessel numbers operating in the area and the number of fishing gear used on each vessel, as well as number of fishing days that the vessel operated each year [26]. This fact facilitates use of the coastal fishing vessel data in ways described below. The reliability of these data is unknown; however the underlying raw data for this period are not available. Similar reports of fisheries data have been considered as reliable in previous studies [26].

Official statistics on number of coastal fishing vessels and most commonly used coastal fishing gear were obtained from available official reports and statistics of the Ministry of Agriculture which are available from 2004. The reliability and accuracy of these data are considered sufficient. Further, reliable quantitative data regarding number of different fishing gears deployed annually were collected from official regulations by the public authorities. Such information is available for period between 2010 and 2023.

2.2. Information on gear loss rates by fishing gear type and estimation of gear loss potential

The information on fishing gear loss rates for each fishing gear type were estimated from earlier research results available in other parts of the world. The data were acquired by applying a systematic literature review method [27]. A systematic review is designed to select, organize and analyze the information acquired using a relevant and systematic search method and aims at minimizing the source selection bias. This procedure was applied in this study as described below.

2.2.1. Data collection and selection of publications

The systematic literature review used in this study consisted of three steps. First, search of the sources using applicable scientific databases, second, selection of the sources that provide relevant information, and third, analysis of selected publications. The literature search was conducted using three scientific search engines, Web of Science, PubMed and ProQuest, for peer-reviewed articles that consider rate of fishing gear loss. All three databases are widely used in systematic literature studies, including reviews in fisheries research [28,29]. Among a variety of existing approaches, Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) which is based on a comprehensive framework and procedure for meta-analyses was used in this study [27].

Our research was not time-limited; therefore, all studies that were fitting the set search terms were included. No geographical boundaries were set for this search. We considered publications in English, corresponding to the language mastered by the research team. Further, we considered such document types as peer-reviewed scientific journal articles, book sections and conference papers. Search terms were designed in groups (e.g., fishing gear or fishing gear type combined with the corresponding loss rate) to retrieve relevant studies. Specifically, we used three groups of keywords. The first group focused on terms related to fishing gears and types of fishing gears relevant to this study. The second group included different terms classifying ALDFG. The third group related to different loss estimates and such terms as “number”, “rate”, percentage”. A publication was selected if it contained at least one keyword from each group in its title or keywords section. A complete list of search terms is presented in Supplementary materials (Table S1).

Once the first step of search was completed in the three databases, we selected relevant publications through abstract search. Specifically, we read abstracts of each publication to assess the relevance of each to our study. Sources that did not contain quantitative information about fishing gear losses were excluded from this review.

The last selection criteria considered the full text of the selected sources. The criteria for selected papers in the systematic review are presented in Supplementary materials (Table S2), which contains information included in the review, such as on subject (i.e., fishing gear types), outcomes (i.e., fishing gear loss rates), and study designs.

2.2.2. Data extraction and analysis

The data from the selected studies were extracted concerning the methods used to estimate fishing gear loss rate; fishing gear type; loss rate; fishing area; marine environment considered. Narrative analysis was performed by tabulating and describing the data. Fishing gear types were used as categories to organize the data within table. Data representing fishing gear loss rates reported in individual experimental studies was extracted in a standardized format for following meta-analysis.

2.3. Meta-analysis and estimation of potential fishing gear losses in the region

By performing the systematic literature review, we aimed to acquire data from number of independent studies, each estimating the loss rate of a specific fishing gear type as a percentage of the total number of that fishing gear type in use (Section 2.2). During meta-analysis, we used a pragmatic approach for estimating potential gear loss in Latvian coastal fisheries based on the information from the systematic literature review for each of the commonly used fishing gear types separately. We used the available quantitative information about the number of fishing gears used in the area during a period between 2010 and 2023, employing the following approach.

We were interested in calculating potential fishing gear losses for each fishing gear type considered for each year separately (i.e., 2010–2023). Specifically, we calculated the estimated gear loss by multiplying the gear loss rate acquired from systematic review results by the total fishing gear (i.e., gillnet sheets) used in commercial coastal fisheries that year. Further, we applied a similar approach for estimating the total gear loss estimate for each fishing gear type separately over the whole period considered. Specifically, the sum of all the annual estimates of gear loss for the full range provided an estimate of the total gear lost over the entire period. The estimations were performed as follows.

The data from the systematic literature review were categorized by fishing gear type regarding the amount of fishing gears lost in percentage from the total number of the specific fishing gear used annually. Thus, for each fishing gear type *i*, the data was assembled in following datasets $_{Pi}$ where each consisted of reported amount of lost fishing gear reported in *n* studies as follows:

$$P_i = \{p_{i,1}, \quad p_{i,2}, \ldots, p_{i, \quad n}\} \tag{1}$$

Considering variations in different estimates of fishing gear loss, it is necessary to estimate confidence intervals. To assess the uncertainties in gear loss rate estimates, we employed bootstrap resampling technique [30]. Using this approach we, first, randomly resampled the data for fishing gear loss rates for each specific fishing gear type separately with replacement to create multiple resampled datasets. Specifically, during the resampling, the loss rate estimates for a specific gear type (i.e., gillnets and entangling nets) were resampled with replacement. This technique involves generating multiple datasets by resampling with replacement from the observed data. We applied 1000 bootstrap iterations and calculated Efron 95% confidence intervals (CIs) [30]. Thus, repeating this resampling scheme 1000 times led to a population of 1000 results for the fishing gear loss rates which were applied to obtain the CIs by sorting the 1000 values and ranking them after their value. Based on this, the lower bound value for the 95% CI limit was obtained by inspecting the value for the bootstrap iteration that was the 25th lowest value and the upper bound CI limit was the one with the 975th value [31]. This estimated loss rate was then multiplied with the number of specific fishing gear type used annually in the coastal areas of Latvia to obtain a potential estimate with uncertainties of the fishing gear losses to considering pragmatic upper and lower bound value for gear losses. Thus, the estimated total number of gear lost in the area for a specific year ($L_{i,\ t}$) was estimated using the resampled percentages ($P_{05,i}$, $P_{mean,i}$, $P_{95,i}$) and the associated annual gear quantity for a specific year *t* (from 2010 to 2023) ($Q_{i,t}$) as follows:

$$\begin{aligned} L_{i,t} &= Q_{i,t} \quad \times \quad P_{05} \\ L_{i,t} &= Q_{i,t} \quad \times \quad P_{mean} \\ L_{i,t} &= Q_{i,t} \quad \times \quad P_{95} \end{aligned} \tag{2}$$

The resulting mean estimates and confidence intervals for individual years were reported as the best estimates of gear loss, the associated uncertainties, and insights into how gear loss rates have evolved over time for each fishing gear type in this fishery. We repeated the same procedure when estimating the total fishing gear loss rates for each fishing gear type separately.

We used the statistical software SELNET for the analysis of the data [32].

2.4. Methodological limitations

Considering the scope of this study, it contained following methodological limitations. First, the study is based on an indirect pragmatic approach calculating the fishing gear losses in the study area. It is based on existing gear loss estimates found in scientific literature and the available information on the amount of fishing gears used in the specific case study. However, estimations of confidence intervals, as presented in this study, allowed to account for variations in different estimations of fishing gear loss. Further, fisheries in this area are performed in particular fishing and environmental conditions in coastal areas, and the results shown in the next section provide an estimate on fishing gear losses in the coastal areas of the Baltic Sea. Therefore, ALDFG resulting from the remaining fishing fleet is not considered in the present study. Use of such case studies are recognized to provide in-depth understanding of complex various complex issues [33]. Therefore, it is possible to use such an application for this study as presented here.

3. Results

3.1. Fishing activities and Latvian coastal fishing fleet

The total numbers of the Latvian coastal fishing fleet as summarized in this study is shown in Table 1. In the early 1990s, the Latvian fishing fleet consisted of 351 fishing and fishery support vessels. Fishing was considered a leading traditional sector in the economy in this region [34]. During this time, the coastal fleet consisted of small tonnage vessels fishing in the Baltic Sea. However, in 1991, when the Latvian Republic became independent, the fishing fleet appeared to be poorly maintained and included many obsolete vessels and vessels in poor condition. Thus, only one third of the vessels was considered worthwhile to upgrade and modernize. Therefore, at the beginning of 1993, there was a decrease in number of fishing vessels and the Latvian fishing fleet numbered 277 vessels (Table 1). Of this total, 198 were coastal vessels that fished only in the adjacent Baltic Sea [34]. The following years, the

Table 1
Summary of the number of registered coastal fishing vessels fishing in Gulf of Riga and along the coast of Latvia.

Year	Total number of fishing vessels in the fleet	Total number of fishing vessels involved in coastal fisheries	Fishing gear type for the coastal fisheries	Source
1991	351	N/A	N/A	Kravanja and Shapiro [34]
1993	277	198	N/A	Kravanja and Shapiro [34]
2004	898	N/A	Mainly passive fishing gear	Ministry of Agriculture [37]
2015	688	610	N/A	Proskina et al. [38]
2016	686	612	N/A	EUROFISH [36]
2018	671	N/A	Mainly passive fishing gear	Ministry of Agriculture [37]
2019	661	605	Mainly passive fishing gear	Ministry of Agriculture [37]
2020	660	603	Mainly passive fishing gear	Ministry of Agriculture [39]
2021	645	598	Mainly passive fishing gear	Ministry of Agriculture [40]
2022	645	598	Mainly passive fishing gear	Ministry of Agriculture [41]

N/A—no information available in the source.

number of coastal vessels increased; however, a further decrease in number of fishing vessels was observed since 2004 (Table 1). Such decrease was associated to fishing capacity reduction schemes [35] that increased the catches for the remaining fleet, thus increasing the profitability [35].

Subsequently, the number of registered coastal vessels remained stable at around 650 vessels during the last years (Table 1), constituting around 90% of the total Latvian fleet in terms of numbers where the remaining belong to the offshore fleet [36]. Most of these are small scale vessels, often with size of up to 5 m in length and without an engine. Therefore, they are constituting 3% of the tonnage and 10% of the capacity of the entire fleet.

3.2. Summary of number of commonly used fishing gear types

Coastal commercial fishermen use various fixed fishing gear types [36] and have been targeting such species as Baltic herring (*Clupea harengus membras*), smelt (*Osmerus eperlanus*), round goby, salmon (*Salmo salar*), sea trout (*Salmo trutta*), vimba bream (*Vimba vimba*), turbot (*Scophthalmus maximus*), eelpout (*Zoarces viviparus*), European flounder (*Platichthys flesus*), and cod (*Gadus morhua*) [42]. Cod has been an important species in the region; however, it has been considered overfished for long periods [43]. Since 2000, sprat (*Sprattus sprattus*) and herring have accounted for a large part (around 90%) of the total annual landings [42]. Most recent information from 2023 show that a total of 653 fishing vessels are registered in Latvia [44] and 92% of them are small boats.

The main fishing gear used are gillnets and entangling nets. The percentage contribution to the fisheries differs slightly between the sources; however, gillnets and entangling nets are often listed among the most common fishing gears used. Specifically, according to EUMOFA [44], gillnets and entangling nets comprise 93% of the fishing gear used in percentage of total number of vessels. The remaining 7% are other fishing gear types. However, the fishing gear use differs considerably between fisheries in Gulf of Riga and along the Baltic Sea coast. According to the Nature Conservation Agency [45], the contribution to total number of gears by gillnets and entanglement nets is estimated to be smaller, 50% for the Gulf of Riga and 63% for the Baltic Sea coastal areas. In addition to that, the source mentions use of seines, stationary uncovered pound nets for herring fishery, and trap gear such as fyke nets which, however, have small contribution to overall used gear types.

Quantitative information regarding fishing gear used in coastal commercial fisheries in the area is available from 2010. Specifically, the Regulations for commercial fishing limits and use in coastal waters [46] specify the number of used fishing gear in coastal waters since 2010 and provide relevant information on the quantity of fishing gears for each fishing gear type used annually. This information is summarized in Table 2. The results showed that gillnets and entangling nets constitute a large proportion of the total amount of fishing gears used, the number being around of over 4000 netting sheets, i.e., netting mesh panels that are commonly deployed connected in fleets [47]. The number of trap gear (fyke nets) deployed in the coastal areas to target different species has been slightly increasing due to introducing use of fyke nets for targeting round goby in 2018 (Table 2). Hook and line fisheries have a considerable contribution to the commercial coastal fisheries sector [46], the number ranging between 51 100–54 600 hooks in the period between 2010 and 2024 (Table 2).

3.3. Fishing gear loss estimates

3.3.1. Search results of the systematic literature review

Systematic literature searches in Web of Science, PubMed and ProQuest databases yielded a total of 212 articles. Sources resulting from the literature search were published between early 1990s up to the present time; however the publication rate was not evenly distributed throughout these years. This shows that the topic has been gaining more attention especially during the last decade, revealing growing interest in scientific field regarding ALDFG (Supplementary material S3).

Table 2
Regulated number of fishing gear for use in commercial coastal fisheries in Latvian territory (Gulf of Riga and coastal fishing areas) from period of 2010–2024.

Year	Stationary uncovered pound nets	Seines (all)	Trap gear (all)	Gillnets and entangling nets (sheets)	Longline hooks
2010	159	8	1084	4003	52,600
2011	159	8	1084	4018	52,600
2012	159	8	1084	4018	52,600
2013	159	10	1094	4093	54,600
2014	159	11	1094	4163	54,600
2015	160	12	1083	4231	54,600
2016	160	12	1082	4236	54,600
2017	160	12	1078	4326	54,200
2018	160	12	1154	4306	53,800
2019	160	12	1152	4175	51,700
2020	166	10	1150	4170	51,100
2021	166	10	1150	4170	51,100
2022	164	10	1142	4209	51,100
2023	162	10	1139	4283	51,100
2024	160	10	1139	4319	51,100

Source: Legal Acts of the Republic of Latvia [46].

After eliminating articles that did not meet one or more of the study criteria (Supplementary material S2), the final data set contained 13 articles (Fig. 3).

The studies selected for full text analysis assessed different topics related to ALDFG. Specifically, some of the studies evaluated only the effect of ALDFG, for example, by simulating ghost fishing. However, such studies did not provide information of total fishing gear loss rates and, therefore, were excluded from further study. Some of the studies provided discussion of potential magnitude of ALDFG; however, without providing any quantitative information. These were also excluded from this review.

From the included studies, we were able to extract information about loss rates of different fishing gear types selected for this study such as trap gear, gillnets and entangling nets. However, potential gear loss when using stationary uncovered pound nets have not been estimated in earlier studies. Full list of included studies is available in Supplementary material S4. These studies covered coastal fisheries in different geographic regions and different fisheries. Some of the studies quantified loss rates for several fishing gear types while some focused only on one specific fishery and fishing gear type. The methods commonly applied to quantify fishing gear loss included statistics summaries and interviews. The results of the systematic literature review are summarized in Table 3.

The estimated loss rates within each fishing gear type varied between fisheries but in few instances also for the same fishery between different studies. Generally, most studies focused on loss rates of passive fishing gear types such as pots and traps and gillnets and trammel nets. Less focus has been on estimating losses in fisheries using active fishing gear like demersal or mid-water trawls or seines; however, one of the studies included loss estimate of this type of fishing gear as a summary estimate from different trawl fisheries globally [48] which was included in the results of our systematic literature review (Table 3). No information for fyke net losses were found in the available literature; however, several studies assessed losses of different trap gear (Table 3).

3.4. Estimated potential fishing gear losses in the region

All loss rates from the reviewed studies were significantly different from zero regarding probability of fishing gear loss for all fishing gear types considered. The results from the systematic review were applied to the number of fishing gears used over the period between 2010 and 2023 to obtain annual estimates of fishing gear losses over time. The results

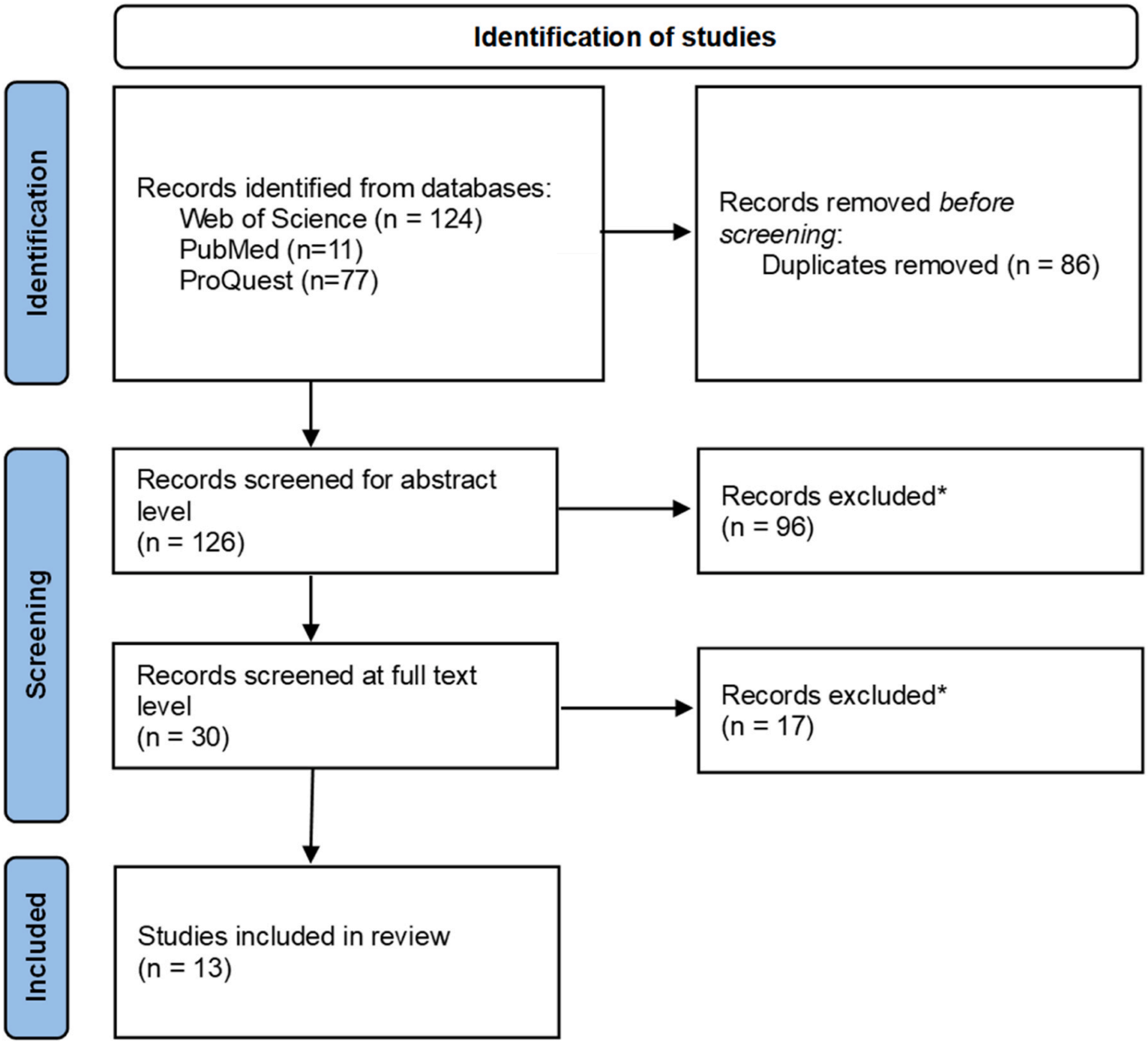

Fig. 3. Study screening and selection. This flow diagram was constructed following Moher et al. [27]. n denotes number of publications. * - records excluded according to inclusion/exclusion criteria set for this study (for detailed information, see Supplementary material S2).

are presented in Fig. 4.

Due to a rather constant number of fishing gears used in commercial fisheries during the period, only small variations were observed in yearly estimated fishing gear losses for all fishing gear types considered. Seine fishery showed a small contribution to gear losses both due relatively small amount of gear used and smaller estimated percentage of loss of this fishing gear type compared to other gears such as gillnets and entangling nets or trap gear.

The results showed that for gillnets and entangling nets, the estimated loss annually varied between 189 (CI: 66–341) to 205 (CI: 72–379) net sheets. For trap gear, the amount varied between 96 (CI: 33–162) and 102 (CI: 35–173) fishing gear lost each year in this coastal fishery. Estimates for longline gear are based on losses of snoods (also called gangion or branch lines), i.e., lines connecting hooks to the mainline [59]. This was due to the available information on amount of used gear only being available in number of hooks. Further, the number of hooks and snoods on each mainline is not constant. Thus, the estimated number of hooks and snoods that can be lost in this fishery was between 2657 (CI: 2381–2938) and 2839 (2544–3139) each year. Annual estimates over the study period allowed further to estimate total loss throughout 2010–2023 for each fishing gear type separately (Table 4).

The results showed that over the considered period in the area, commercial small scale coastal fisheries resulted in estimated 2762 (CI: 969–4976) lost nets, including gillnets and trammel nets, and 1379 (CI: 473–2337) lost trap gear, including fyke nets. Resulting marine pollution from longline fisheries through hook and snood loss was estimated to 38,496 (CI: 34,498–42,576) over the considered period. Since no information in the literature search provided any estimates on loss of stationary uncovered pound nets, it was not possible to estimate loss rates of this fishing gear.

4. Discussion

In this study, we have recovered and analyzed historical and recent information on number of fishing vessels involved in coastal fisheries and number of different fishing gear types used in coastal areas of Latvia, specifically, the Baltic Sea coast and the Gulf of Riga. Further, we have combined it with results of a systematic literature review on the available specific fishing gear loss estimates and applied this to estimate fishing gear losses in this enclosed marine area for period between 2010 and 2023. By using this approach, we have derived a picture of the potential magnitude of the fishing gear losses in this area which previously has not been investigated.

The results of this study showed that such fishing gears as gillnets and entangling nets, as well as trap gear, including fyke net different configurations can have a considerable contribution to overall gear loss in the area. Such passive fishing gear can show a considerable risk for

Table 3
Fishing gear loss rate by gear type: results of the systematic review.

Fishing gear type	Loss rate (%)	Region	Target species	Seabed substrate type	Depth (m)	Year	Source
Gillnets, entangling nets, trammel nets							
Demersal gillnets and entangling nets	1.52%	Turkey, Black Sea	Multi-species	N/A	N/A	2015	Dagtekin et al. [49]
Demersal gillnets	1.31%	Turkey, Black Sea	Turbot (*Scophthalmus maximus*)	N/A	100	2015	Dagtekin et al. [49]
Trammel nets	3.09%	Turkey, Black Sea	Whiting (*Merlangius merlangus*)	N/A	100	2015	Dagtekin et al. [49]
Drift nets	0.85%	Turkey, Black Sea	Bonito (*Sarda sarda*)	N/A	N/A	2015	Dagtekin et al. [49]
Trammel nets and demersal gillnets	1.23%	Turkey, Black Sea	Red mullet (*Mullus barbatus*)	N/A	N/A	2015	Dagtekin et al. [49]
Demersal gillnets	0.84%	Turkey, Eastern Mediterranean	Multi-species	Sandy-rocky	5–36	2007	Ayaz et al. [50]
Trammel nets	3.41%	Turkey, Eastern Mediterranean	Multi-species	Sandy-rocky	5–36	2007	Ayaz et al. [50]
Gillnets	0.81% (0.62–1.00%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Trammel nets	8.47%	Turkey, North-Eastern Mediterranean	Shrimp	Sandy, rocky	10–65	2007–2008	Ozyurt et al. [51]
Trammel nets	8.54%	Turkey, North-Eastern Mediterranean	Sole	Sandy, rocky	10–65	2007–2008	Ozyurt et al. [51]
Gillnets and trammel nets	18.80%	Turkey, North-Eastern Mediterranean	Multi-species	Sandy, rocky	30–50	2007–2008	Ozyurt et al. [51]
Trap gear							
Pots and traps	0.50–2.00%	Atlantic Canadian fisheries	American lobster (*Homarus americanus*) and snow crab (*Chionoecetes opilio*)	N/A	N/A	2021	Goodman et al. [52] McIntyre et al. [53]
Pots and traps	0.74% (0.63–0.85%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Traps	2.00–5.00%	Florida, USA	Spiny lobster (*Panulirus argus*)	Hard surface	N/A	2016	Uhrin [54]
Traps	2.33%	Washington, USA	Spot prawn (*Pandalus platyceros*)	Sand, rock	32–107	2018	Antonelis et al. [55]
Pots	20%	Virginia, USA	Blue crab (*Callinectes sapidus*)	N/A	<2 to >6 m	2014	Bilkovic et al. [56]
Pots	18%	Florida, USA	Spiny lobster (*Panulirus argus*)	Sandy, rocky	N/A	2014	Uhrin et al. [57]
Traps	8.60%	Washington, USA	Dungeness crab (*Cancer magister*)	N/A	N/A	2011	Antonelis et al. [58]
Trawls							
Trawl nets (all)	3.57% (2.71–4.43%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Bottom trawl	3.94% (2.96–4.91%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Midwater trawl	0.76% (0.14–1.38%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Seine nets							
Seine nets	1.51% (1.09–1.93%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Longlines, line and hook fisheries							
Mainline	3.33% (2.78–3.96%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Snood line	3.58% (2.80–4.36%)	General estimate	General estimate	N/A	N/A	2021	Richardson et al. [48]
Snood line	5.75% (2.75–9.83%)	Croatia	Multi-species	Rocky substrate	33.0–64.7 m	2023	Cerbule et al. [22]
Snood line	4.66% (3.84–5.46%)	Norway	Haddock, cod	N/A	100–240 m	2022	Cerbule et al. [21]

N/A—no information given in the source. Values in parentheses for loss rate denote 95% confidence intervals if provided in the source. Year denote time when the experiments were conducted or, in absence of this information, year of the publication.

ghost fishing due to being designed to catch marine animals when set at sea unattended, corresponding to a situation when the gear is abandoned, lost, or otherwise discarded [12].

Our study showed that the estimated loss from commercial coastal small-scale fisheries in the area over the last decade alone could have resulted in loss of 1379 (473–2337) lost trap gear and 2762 (CI: 969–4976) gillnet and entangling net sheets. Considering that these fishing gear types are designed to capture marine animals unattended [60], such lost gear, accumulated over the last decade, could contribute to ghost fishing. Ghost fishing in such passive fishing gears can potentially continue for long periods, i.e., until the gear is either found and removed or when it is eventually degraded to a state where all animals can escape [61].

Further, a considerable loss potential from longline fisheries was observed with 38,496 (CI: 34,498–42,576) hooks and snoods lost over the study period. Due to lack in data availability, we were not able to estimate loss of whole mainline in this fishery. However, accounting for loss in snoods in this fishery is important considering that a fraction of

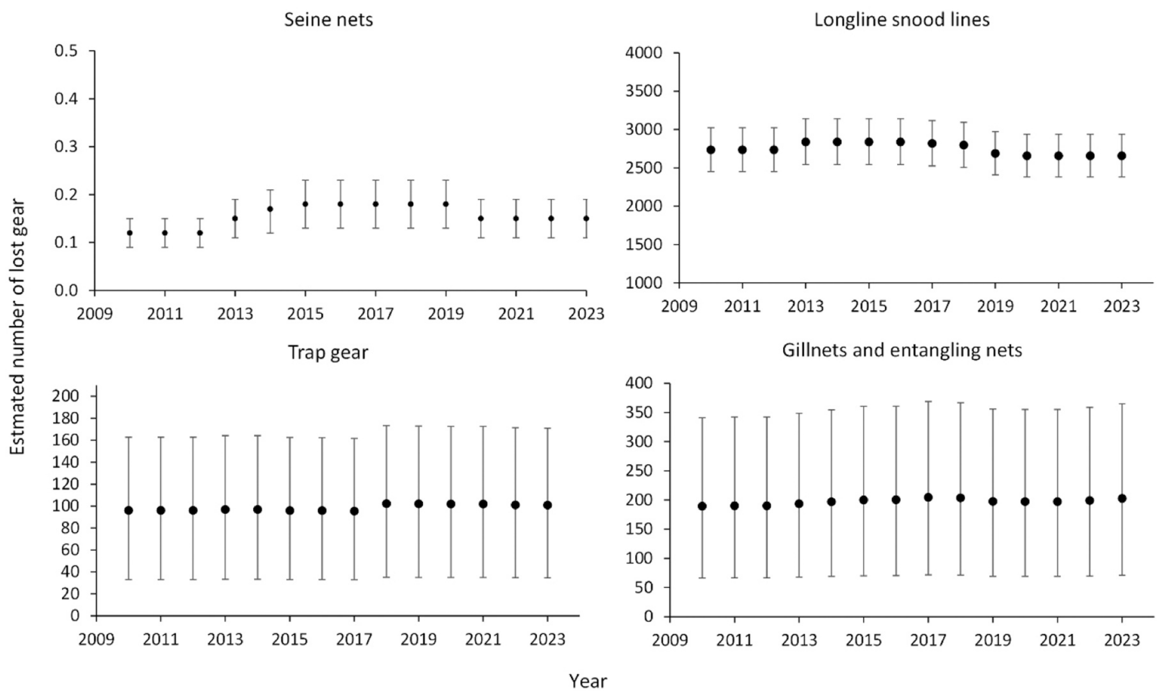

Fig. 4. Estimated mean annual fishing gear loss for each of the fishing gear types used in the Gulf of Riga and coastal areas of Latvian territory (circle marks) with 95% confidence intervals. The upper left plot shows the annual number of seine loss. Upper right plot shows estimated loss of longline snood lines. Lower row shows the loss estimates for different trap gear (left) and gillnets and entangling nets (right).

Table 4
Estimated mean total loss of different fishing gear types throughout the period of 2010–2023 for each fishing gear type.

Gear type	Estimated loss rate
Seines	2.18 (1.59–2.76)
Gillnets and entangling nets	2 762.37 (969.46–4 975.77)
Trap gear	1 379.48 (473.32–2 337.04)
Longline snood lines	38 495.60 (34 497.98–42 576.25)

snoods can be lost during each gear deployment [2,21,22]. In many longline fisheries, similar to the fishery observed in this study, snoods are made from polyamide (nylon) material [21,22,62]. Longline mainline or snood loss do not present the same risk for continuous ghost fishing as, for example, gillnets and entangling nets or traps [7]. However, since these gear parts are often made of plastic materials, they contribute to marine plastic pollution in case of gear losses [21,22]. Our results showed minor potential contribution from lost seine nets which is in accordance with earlier studies stating that the highest risk is associated to passive fishing gear types [12].

The information provided in this study is an approximate estimate of the total gear losses since the extent of losses and associate potential for ghost fishing is usually specific for each fishery [7]. Specifically, fishing gear loss rates can differ between various fisheries in different geographic areas due to specific gear types, marine environment and target species [2,25]. Similarly, in addition to plastic pollution, the ghost fishing efficiency by such lost gear can be varying. However, given the missing information in the region and absence of systematic clean-up operations, this estimate can provide a valuable information for different management institutions. Specifically, it can serve as a baseline regarding the potential magnitude of fishing gear losses that can be associated to marine plastic pollution and potential ghost fishing risk in this region. Specifically, the estimated loss of fishing gear between 2010 and 2023 is related to loss of gear that is made of mainly non-biodegradable plastic materials, since that has been commonly used material in different fishing gear types. In this study we utilized the available quantitative information on commercially used fishing gear over last decade, i.e., starting from 2010. However, the number of coastal commercial fishing vessels and associated fishing activities have been constant for a longer period (Table 1), potentially resulting in comparable levels of gear loss as quantified for the last decade. Considering that the fishing gear made of non-biodegradable plastic materials can remain in the marine environment for decades [5,6], the magnitude of ALDFG present in this area, therefore, might be higher.

Earlier observations of ALDFG occurrence in the southern part of the Baltic Sea showed that remains of ALDFG were not recorded in areas deeper than 80 m [16]. However, in different parts of the Baltic Sea, the level of ALDFG abundance may differ considerably due to absence or presence of previous clean-up operations. Specifically, in case of southern Baltic Sea and Polish waters of the area, previous intensive ALDFG clean-up operations removed 300 tonnes of ALDFG since 2014 [63]. This huge amount of removed gear in other areas further highlights the potential scale of the problem in other areas of the Baltic Sea. In Latvian part of the Baltic Sea and the Gulf of Riga, no such previous comprehensive clean-up programs have taken place; therefore, the assumed benthic ALDFG litter can be considerable. The results from pilot clean-up operations demonstrated that ALDFG can persist in marine environment in the Baltic Sea for longer periods, and cause ghost fishing after decades of being lost [24]. This observation is contrary to the results presented in Brown and Macfadyen [7] that nets lost on wrecks tend to rapidly degrade over time limiting the ghost fishing within months. Furthermore, this result differs from results of FANTARED project that showed that the ghost fishing time in most cases does not exceed 6–12 months by lost fishing nets [64].

Up to date, the clean-up operations conducted in the area have been restricted to beach marine litter monitoring [65]. This study found that nationally, the average amount of plastic and polymer materials was 53% of the total amount of litter found, exceeding all the other litter categories [65]. However, this includes all litter sources, i.e., also various household items and other plastic disposables. Although such effort is crucial since part of the ALDFG indeed can end up as beach litter [11], this would not reduce the benthic ALDFG in the marine environment and other approaches for clean-up operations such as ALDFG retrieval operations [66] are crucial.

1995 FAO Code of Conduct for Responsible Fisheries [67] recognizes the impact of ALDFG. It states that the states are responsible for taking necessary measures to minimize the negative ALDFG related effect. Further there are other international documents expressing the need to limit the negative environmental effect by such lost fishing gear. Considering the estimated scope of the fishing gear loss rates in this area over the last decade, this has a potential to cause considerable negative effect on the marine environment, and thus efforts to minimize the amount of lost gear are necessary.

Information about fishing vessels in this study is based on available information of registered boats based on official fisheries data. Such official data are not accounting for the total fisheries activities as part of illegal, unreported and unregulated fishing (IUU) [68] and loss, abandonment and discards of the associated fishing gear. The lack of overview over such activities implies that the estimated amount of ALDFG can be larger if estimates of such gear resulting from IUU activities would also be considered. Such data, however, remains unavailable. Zeller et al. [15] aimed to account for IUU fishing activities when considering the total fisheries removals in the Baltic Sea region during period of 1950–2007 using catch reconstruction. They estimated that unreported landings, and, therefore, potential part of associated fisheries activities in this area added 14% to the reported landings between 1950 and 2007. Further, the fishing gear loss estimates provided in this study do not include recreational fisheries. Little information exists on recreational fisheries in most Baltic Sea countries [15], especially historical statistics. This lack of data hinders assessing this sector's impact on the ecosystem regarding ALDFG. However, the contribution to ghost fishing gear from this sector through lost, abandoned or otherwise discarded fishing gear could be considerable and would need to be estimated in future studies.

5. Conclusions

Information of the amount of ALDFG in different marine areas is crucial for estimating the extent of this environmental and socioeconomic challenge, and for developing appropriate management measures. This is especially the case for enclosed or semi-enclosed environments where reducing of marine pollution is of special importance [16]. Our study demonstrated application of a pragmatic approach for estimating fishing gear loss in absence of other information on annual gear loss in a specific fishery. Estimation of confidence intervals allowed us to account for variability in earlier fishing gear loss estimates. In future studies, similar approach can be applied in other areas to quantify fishing gear loss over time considering precautions stated above. Such information can further contribute to improve our understanding on gear loss and necessary management measures to improve fisheries sustainability.

CRediT authorship contribution statement

Astrida Rijkure: Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Janis Megnis:** Writing – original draft, Investigation, Conceptualization. **Kristine Cerbule:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106187.

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