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Sources, pathways, and abatement strategies of macroplastic pollution: an interdisciplinary approach for the southern North Sea

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The issue of marine plastic pollution has been extensively studied by various scientific disciplines in recent decades due to its global threat. However, owing to its complexity, it requires an interdisciplinary approach to develop effective management strategies. The multidisciplinary scientific approach presented here focuses on understanding the sources and pathways of macroplastic litter and developing abatement strategies in the southern North Sea region. Over 2.5 years, more than 63,400 biodegradable wooden drifters were deployed with the help of citizen science to study the sources, pathways, and accumulation areas of floating marine litter. Rivers act as sinks of most of the floating marine litter released within their waterways. Short-term field experiments were also conducted to analyse the hydrodynamic and atmospheric processes that govern the transport of floating litter particles at the sea surface. Numerical models were used to examine the transport of virtual litter particles in the entire North Sea and in coastal regions. It was found that there are no permanent accumulation areas in the North Sea, and the Skagerrak and fronts can increase the residence times of floating marine litter and favour sinking. Field surveys revealed that the majority of litter objects originate from fisheries and consumer waste. To develop effective abatement strategies, the key stakeholder landscape was analysed on a regional level. The interdisciplinary approach developed in this study highlights the importance of synergizing scientific resources from multiple disciplines for a better understanding of marine plastic pollution and the development of effective management strategies.

KEYWORDS

floating marine litter, abatement measures, stakeholder interactions, numerical modelling, German Bight, coastal ecosystem, drifters, citizen science

1 Introduction

Anthropogenic litter, which presents a major threat to marine and coastal ecosystems, is reported worldwide (Wilcox et al., 2015; Canals et al., 2020; MacLeod et al., 2021). Plastic generally constitutes the majority of litter found in the oceans and along shorelines (Derraik, 2002; Barnes et al., 2009; Lebreton and Andrady, 2019). Global plastic production has increased from 1.7 million tons in the 1950s (Plastics Europe, 2013) to 391 million tons in 2021 (Plastics Europe, 2022), and is expected to double over the next two decades (European Commission, 2018). Jambeck et al. (2015) estimated that between 4.8 and 12.7 million tons of plastic litter entered the oceans from global coastlines in 2010 alone and predicted a sharp increase in the next decade without effective prevention strategies. Once entered the marine environment, floating and suspended plastics are distributed by a number of hydrodynamic and atmospheric processes (Röhrs et al., 2012; van Sebille et al., 2020). In addition, biological and chemical mechanisms, such as ingestion, settlement, and degradation impact the plastic budget and distribution in the oceans (Wilcox et al., 2015; Koelmans et al., 2017). The United Nations Environment Assembly and the G20 Leaders have declared marine litter a major global issue, confirming the need to tackle this form of anthropogenic pollution. Thus, understanding the dynamics of litter in the marine environment and developing effective abatement strategies is a multi-faceted challenge and must be considered from the perspective of various scientific disciplines (Vince and Stoett, 2018).

Coastal regions are often crucial for the national economy and various anthropogenic stressors contribute to local marine pollution. The interests of various stakeholders tend to be heterogeneous (NOAA, 2015) and local populations' awareness and perception of marine pollution issues vary widely (Beeharry et al., 2017). In addition, the hydrodynamic variables that influence the distribution and accumulation of marine litter depend heavily on regional currents, geomorphological features, and local meteorological conditions. Willis et al. (2017), Stanev and Ricker (2019) as well as Schöneich-Argent and Freund (2020) indicated that the majority of land-based marine debris in coastal regions is deposited close to its source. Considering these aspects, research is expected to be expedient when targeted at mitigation of marine litter pollution through an interdisciplinary scientific strategy that considers the interrelation of regional socio-economic, ecologic, and hydrodynamic aspects of the problem in a regional context. The southern North Sea is one of the most intensely used coastal areas, connecting Europe's major ports with the world's oceans. The coastal region is exposed to various anthropogenic pressures and is of great economic, political, and ecological importance for Europe.

To develop a comprehensive understanding of macroplastic pollution (objects >5 mm in size) in the southern North Sea, a consortium of multi-disciplinary marine scientists, geographers, and environmental planners was formed. This article reviews research activities (schematically shown in Figure 1) conducted by the multidisciplinary consortium considering the pollution of the southern North Sea area from various scientific viewpoints. The researchers surveyed marine litter at the coast, estuaries, and seafloor to better understand the distribution and transport of litter in the area. They also conducted *in-situ* measurements and experiments with drifters to study the hydrodynamic effects on litter and used numerical modelling to understand the oceanographic processes that govern their movement.

The findings of this research were merged with a detailed analysis of the stakeholder landscape in the German North Sea,

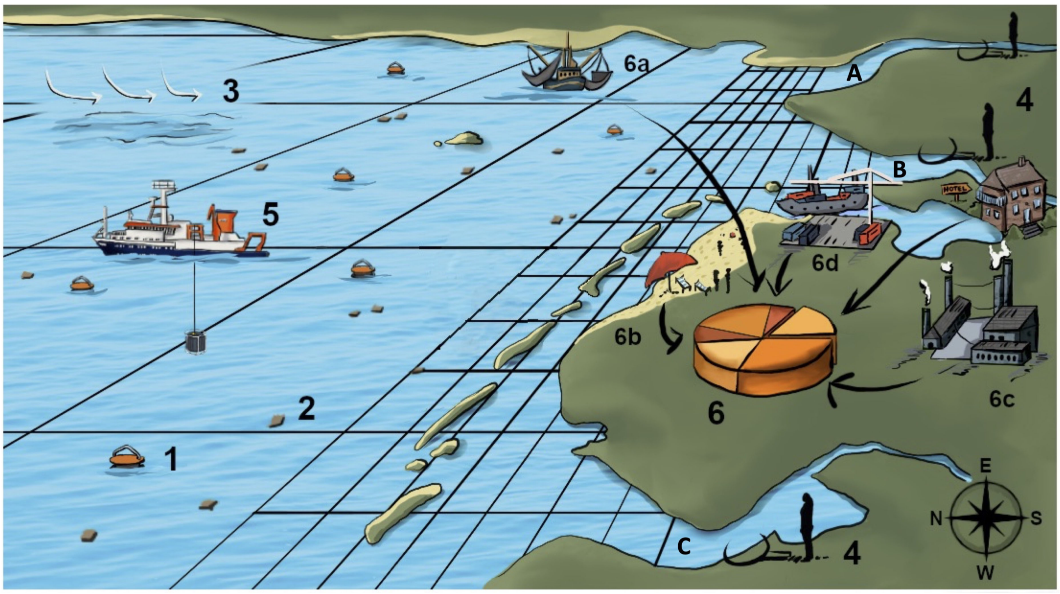

FIGURE 1
Schematic illustration of the research activities conducted by the consortium in the German Bight. The tributaries are marked with bold letters: Elbe **(A)**, Weser **(B)**, and Ems **(C)**. Numerical grids are shown as black boxes with increasing lateral resolution towards the coast. Satellite-tracked surface drifters (1) are shown in orange and the wooden drifters (2) are displayed as small brown plates. Hydrodynamic and atmospheric forces (3) are exemplarily shown in the illustration. River monitoring sites are indicated with small person (4). Research activities such as bottom trawling and the collection of *in-situ* hydrodynamic data are represented by the research vessel (5). The stakeholder analysis is shown with the pie chart (6) including the interests of various stakeholders (fisheries (6a), tourism (6b), industry (6c), and harbour activities (6d)).

providing a comprehensive view of the issue from both scientific and societal perspectives. This review aims to provide not only scientific knowledge, but also to serve as an exemplary framework for policymakers, stakeholders, and citizens. The interdisciplinary approach of the research consortium is highlighted as an important aspect of the study.

2 Sources

Many studies on marine litter describe its occurrence in specific regions or simulate its pathways and possible sinks (e. g. Barnes et al., 2009; Lebreton et al., 2012; Ryan, 2014; Cózar et al., 2015). However, to accurately predict and sustainably reduce marine litter, sources have to be identified. Although examples for other regions exist in the literature (e.g. Veiga et al., 2016), such investigations are still scarce. Even fewer studies are available for the North Sea (Schulz et al., 2015a; Huwer et al., 2017; Gutow et al., 2018; Schäfer et al., 2019).

To locate major litter input sites along the Lower Saxony coastline and its three major rivers Ems, Weser, and Elbe, a range of potential litter source points were identified through a web- and map-based search (Schöneich-Argent et al., 2020) (Figure 2A). Ultimately, seasonal releases of a total of ~63,400 wooden drifters were conducted over 2.5 years (October 2016 – March 2019) to simulate sources of floating marine litter (FML), building on the experimental drifter approach of Carson et al. (2013). In addition to fifteen land-based locations, several offshore release sites were selected by the physical oceanographers based on regional hydrodynamic conditions. To collect data of wooden drifter reports, an online portal was created, allowing the public to register their findings which were subsequently displayed in an interactive map together with some basic statistics (see Aden, 2019 and Aden and Stephan, 2017 for technical details). The report rate of ~43% (~27,000 validated wooden drifter reports until July 2019) emphasises the significant role that citizen scientists can play in the generation of large data sets (Carcia-Soto and van der Meeren, 2017). Wooden drifter findings are shown as yellow dots in Figure 2B. In this context, the wooden drifters released from riverine sites appear to have provided particularly valuable information as to the role of German North Sea tributaries as

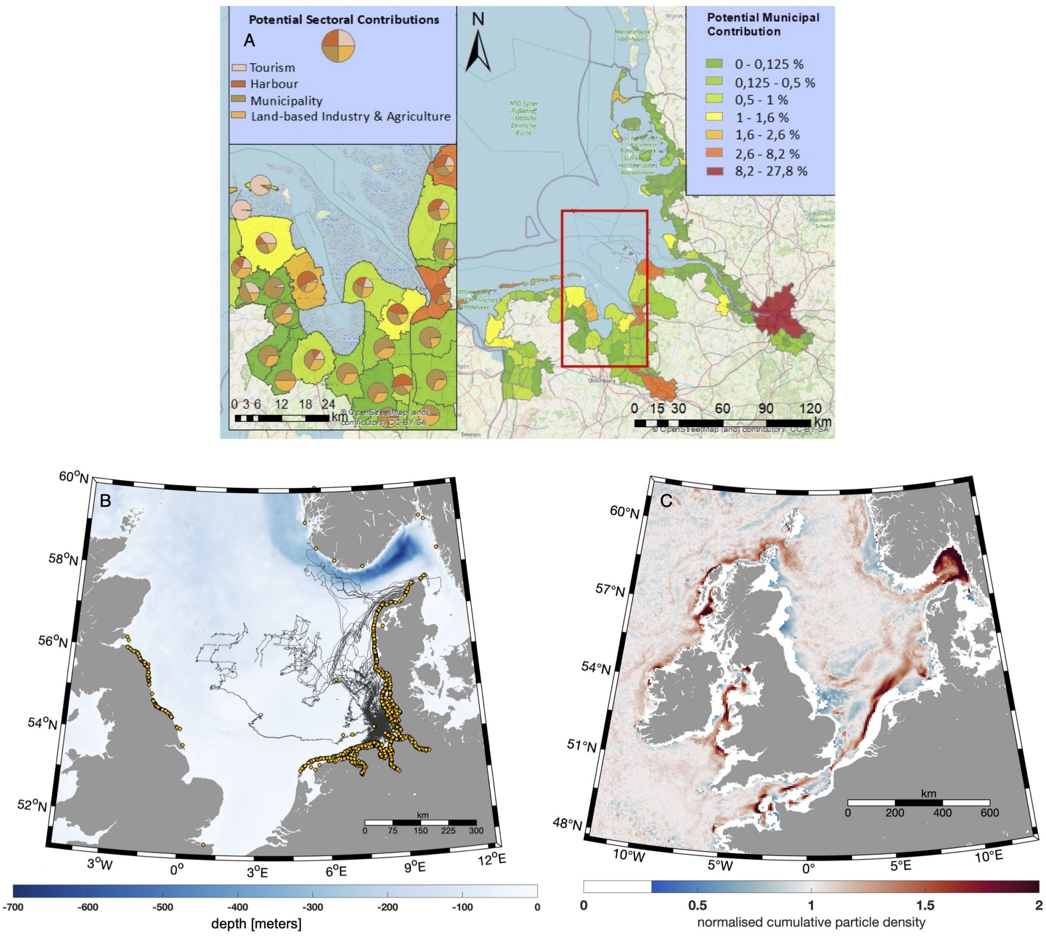

FIGURE 2
(A) Potential municipal contribution of coastal litter input in the German Bight. The zoom also shows the contribution from specific sectors. **(B)** A map of the North Sea is shown, displaying the bathymetry information with colour-shading. The locations of ~27,000 validated wooden drifter reports are marked with yellow dots, and the trajectories of satellite-tracked surface drifters are indicated by black lines. **(C)** Yearly average of normalised cumulative particle density (NCPD) at the surface computed from monthly maps obtained from virtual particle release experiments in 2015 showing the tendency of particle accumulation (NCPD>1) and dispersal (NCPD<1) (adapted from Ricker and Stanev (2020)).

sources or sinks of man-made debris. This was later supported by Schöneich-Argent & Freund (2020), who found 46%, 76%, and 86% of the wooden drifters released in the Elbe, Weser, and Ems, respectively, to have been reported within each waterway. Additionally, based on holistic riverine litter surveys, Schöneich-Argent et al. (2020) estimated that <1% of the total mismanaged plastic waste per catchment (see Lebreton et al., 2017; Schmidt et al., 2017) is emitted by these three North Sea tributaries. It also turned out that a large portion of litter objects likely originates from close-by-sources (Schöneich-Argent and Freund, 2020; Schöneich-Argent et al., 2020; González-Fernández et al., 2021).

To provide a comprehensive overview of potential marine litter sources along the German North Sea coastline, a GIS-analysis was conducted using data of municipalities along the coast and river mouths of the southern North Sea. Hotspots of plastic pollution were specified according to the level of potentially polluting human activities and the contribution of litter input by each municipality was determined. A study by the *Regional Planning and Environmental Research Group* (ARSU), Oldenburg, Germany provided the estimated contribution of each source to the total marine litter pollution in the North Sea (Schäfer et al., 2019). Using results from this study a GIS-based model was created that enabled the comparison of the "pollution probability" of all coastal municipalities, determining potential source regions (Figure 2A, red- and orange-coloured municipalities) and the corresponding sectoral contributions (Figure 2A, pie charts).

Sources of observed FML in the German Bight were assessed by using a numerical hydrodynamic in combination with a Lagrangian model (Gutow et al., 2018). Numerical backtracking of observed objects revealed that its origin differs depending on the object's position with respect to a dominant salinity front in the German Bight. The objects can be split into an offshore (west of the front) and a nearshore (east of the front) cluster. The main contribution of the nearshore cluster originates in Germany (47-61%), followed by the Netherlands (37-45%), whereas the contribution of other countries is negligible. The primary sources of the offshore cluster in turn are Great Britain (21-34%), France (17-31%) and the Netherlands (15-23%), whereas the ranges of percentage contribution depend on the chosen wind drag (0-1%).

To determine the sources of seafloor litter, two bottom trawl surveys were carried out in the south-eastern North Sea. Generalised additive models were used to gain an insight into the driving forces by searching for interrelations between anthropogenic factors, hydrodynamic parameters, and the abundance of benthic marine litter. The results indicate a substantial majority of 97.7% of plastics of all identified litter items and suggest a statistical interrelation of plastic abundance and hydrodynamic variables such as salinity gradients and temperature gradients associated with estuarine fronts in the southern North Sea region (Meyerjürgens et al., 2022). These findings are in line with previous findings of seabed litter abundance in the southern North Sea (Gutow et al., 2018).

In-situ collection of marine litter showed that the majority of the objects originate from fisheries for offshore seafloor litter (Gutow et al., 2018), coastal waters (Meyerjürgens et al., 2022), and river beds (Schöneich-Argent et al., 2020), whereas consumer waste dominate the river columns, surfaces and banks. However, approximately the half of the river litter could not be related to specific sources. The identification of fisheries being the main litter source of the North Sea region is supported by earlier reports of Galgani et al. (2000) and Schulz et al. (2015b).

3 Pathways and accumulation areas

The pathways of floating marine litter are influenced by a complex interaction of hydrodynamical and meteorological conditions (van Sebille et al., 2020). Understanding the role of these factors is a crucial step towards identifying potential accumulation zones in the marine environment.

The report data on wooden drifters indicated that both the distance travelled and coastal accumulation points showed spatial and temporal variability (Schöneich-Argent and Freund, 2020). This variability is similar to what has been observed in the quantities and composition of debris along rivers and coastlines in the south-eastern North Sea region (Schöneich-Argent et al., 2019; Schöneich-Argent et al., 2020). Wooden drifters deployed offshore travelled the farthest, while two thirds of coastal and riverine wooden drifters beached within 25 km and almost 80% within 50 km of the release site. The analysis showed that 28.6% of offshore drifters covered at least 100 km, 69.1% were found within up to 250 km, and 87.4% were first reported within 500 km.

While the release sites of the wooden drifters at presumed litter source points and their finding locations have been recorded, the exact drift paths of the floats remain unknown. To partially fill this knowledge gap, deployments of the wooden drifters were regularly combined with low-cost satellite-tracked buoys developed for tracking the propagation of floating litter items (Figure 2B, black lines) (Meyerjürgens et al., 2019). The satellite-tracked surface drifter is designed to represent the floating behaviour of marine litter of various shapes and floating characteristics. The results of several surface drifter deployments show that floating objects respond strongly to the local wind conditions (Meyerjürgens et al., 2019). In particular, several studies found that wind (Stanev et al., 2019; Ricker and Stanev, 2020) and wind-induced waves (Stanev & Ricker, 2019; Stanev et al., 2019; Staneva et al., 2021) have a strong impact on the pathways and accumulation zones of floating objects at the sea surface. During an extended period of exceptional strong easterly winds throughout February and March 2018, wooden drifters and surface drifters were deployed in the south-eastern North Sea and washed ashore on the British east coast (Figure 2B). Lagrangian numerical experiments were carried out with an accurate calibration using wooden drifter reports and trajectories of surface drifters. These virtual drifter data demonstrated that the circulation of the North Sea was reversed for 1.5 months. It was also shown that in shallow seas strong wind does not only affect the sea surface but also deeper layers down to the sea bed inducing even basin-scale water mass transport. Such wind dynamics may also reverse litter transport and contribute significantly to beaching and redistributing of floating objects during such weather events.

Experiments with surface drifters and simulations with virtual Lagrangian particles have shown the convergence of drifters being enhanced at hydrodynamic density fronts (Meyerjürgens et al., 2020; Ricker et al., 2021), which is also in line with an increased litter abundance of seafloor litter in these regions (Meyerjürgens et al., 2022). Dispersion and diffusivity properties derived from surface drifter observations (Figure 2B, black lines) provide evidence that tides have a scale-dependent effect on the drifter diffusivities (Meyerjürgens et al., 2020). In coastal waters and estuaries, tides have a significant impact on circulation and turbulent processes, and thus also on the dispersal of marine litter (Ricker et al., 2022). The results of numerical simulations demonstrate that the length of the pathways of virtual particles increases by approximately 40% including tides in numerical simulations (Stanev and Ricker, 2020). Furthermore, particle accumulation areas are dynamic in the presence of tides (Ricker and Stanev, 2020). These particle simulations are also used to get a more comprehensive insight into litter pathways on the European Northwest Shelf (Ricker and Stanev, 2020). On monthly time scales, surface-released particles form seven accumulation areas along thermohaline fronts on the shelf (dark red areas in Figure 2C) with varying presence in space and time. Dispersal areas mainly occur in coastal regions (blue areas in Figure 2C). On larger time scales, the Bay of Biscay is also an attractor for surface particles but no permanent accumulation areas form in the region of the North Sea. In contrast, bottom-released particles do not show distinct accumulation areas. Only the Skagerrak accumulates particles at both the surface and bottom. Vertical velocities are also observed to influence the particle trajectories. Notably, the prevailing westerlies induce a significant vertical circulation along the coasts as well as on-shelf transport of surface-released particles. This modelling approach which enables the detection of FML accumulation patterns was also adopted to the Black Sea (Stanev and Ricker, 2019).

Further numerical experiments were conducted to simulate the pathways of multi-annual macrolitter observations in the southern North Sea (Gutow et al., 2018). Forward simulations of observed macrolitter objects revealed that they drift with the mean North Sea circulation from the German Bight into the Skagerrak, potentially recirculate there, and eventually float into the Atlantic *via* the Norwegian Coastal Current. The prevailing westerlies favour a beaching of the floating objects on the Danish and Norwegian coasts. Furthermore, the residence time in the wider North Sea is higher compared to the German Bight. Especially, the Skagerrak can retain objects throughout the water column, whereby long residence times and low beaching probability are expected to favour sinking of floating litter (Holmström, 1975).

4 Abatement strategies and awareness

Understanding the sources and pathways of marine litter is an important step towards its reduction. Equally important is the development of abatement strategies. To this end, a stakeholder analysis was conducted in the southern North Sea region to identify the individuals, organizations, and institutions involved in the marine litter stakeholder landscape.

The stakeholder analysis categorised the stakeholders into sectors and summarised the information into thematic clusters. Seven types of interventions to reduce marine litter were identified through the analysis, which included both land-based and sea-based measures. These interventions were assessed using a multi-criteria analysis (MCA) that evaluated their effectiveness, acceptance, and feasibility. This approach uses consistent criteria to compare alternatives and determine the most promising options; concurrently, it can uncover possible limitations of mitigation approaches (Dodgson et al., 2009). Criteria included, e.g., the necessary time frame to implement a strategy, acceptance within the sector, implementation costs, and the probability of success in reducing marine litter.

The analysis revealed that requirements to minimise plastic in tenders for municipal events were the most promising strategy to reduce land-based pollution. Stricter regulations for storage conditions at harbour sites received the highest total score among sea-based measures, which is especially important given that port operation alone is responsible for an estimated 8% of plastic waste entering the North Sea (Schäfer et al., 2019). The study also highlighted the need for uniform regulations, such as the European “Port Reception Facilities Directive (PRF)” to address the issue of marine litter at the international level.

In addition to these measures, awareness campaigns (e.g. “Ocean Plastic Labs”; https://oceanplasticslab.net) and clean-up efforts were identified as important strategies for reducing marine litter. The study emphasised the importance of involving stakeholders from different sectors and levels of governance in a comprehensive and collaborative approach to address the issue of marine litter in which the fisheries should be more involved. This requires the creation of an overarching legal and regulatory framework at the national and international levels, along with local or regional abatement strategies. Positive public feedback on wood drifters and increasing awareness of the litter problem were identified as promising developments that can contribute to the success of these efforts.

5 Summary

This paper summarises the main results of interdisciplinary research activities aimed at understanding the sources, dispersal, and accumulation dynamics of litter pollution to develop effective mitigation strategies for tackling this issue in the southern North Sea region. Long-term beach and riverine litter datasets were analysed to form a clear picture of the litter pollution levels along the German North Sea coastline. Potential sources were identified by analysing regional stakeholder activities in the southern North Sea area, which were taken into account for determining deployment sites of ~63,400 wooden drifters. They were used as a biodegradable approach, simulating macroplastic litter to determine the pathways of macroplastic litter objects. The beaching locations of the drifters were reported by local citizens, which significantly increased the awareness for marine pollution in the project’s focus region. Multiple field experiments were conducted to understand the hydrodynamic drivers of the pathways, distribution, and accumulation of marine litter in the region. The collected data were used to develop and validate numerical models which, in turn, contribute to a clearer picture of multi-annual transport and accumulation patterns in the North Sea. With the involvement of local stakeholders, a multi-criteria analysis was conducted to assess the benefits in terms of effectiveness, acceptance, and feasibility of specific mitigation strategies for the German North Sea coast. However, more effort should be put into awareness-raising campaigns in the fishing sector, as this is the main source of marine litter found in field surveys. In addition to these results, this paper provides an overview of how interdisciplinary work, also including citizen participation, can be designed to sensitise the general public to ecological and socio-economic challenges.

Through four years of interdisciplinary work on marine litter in the North Sea, combining different research approaches and expertise from various scientific fields has allowed for a more comprehensive understanding of the sources, pathways, and potential abatement for this environmental threat. This approach is likely to be beneficial for finding solutions to this issue in other regions or on a global scale. Future research should concentrate on specific aspects of marine litter, such as their underlying physical processes, sources and input rates, dispersal, and accumulation at the sea surface and sea floor.

Author contributions

JM and MR prepared the manuscript with substantial contribution from all authors. THB structured and streamlined the draft and MA, JM, MR, and JB prepared the figures. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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