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Research article

Renewable energy caves: water replenishment holes in offshore monopiles create novel marine habitats

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ABSTRACT

The expansion of offshore renewable energy introduces artificial hard substrate, but the ecological effects may change depending on design features. For example, water replenishment holes, implemented for internal water refreshment and corrosion control, also allow colonisation of previously inaccessible monopile interiors, creating a novel semi-enclosed habitat. This study compared epifaunal communities on the interior and exterior walls of four water replenishment hole-equipped monopiles in the southern North Sea and modelled internal water quality to better understand factors shaping these communities. Vertical video transects were used to quantify percentage cover along depth gradients, while a coupled hydrodynamic-water quality model predicted vertical patterns in dissolved oxygen and particulate organic carbon over one year. Monopile interiors function as semi-enclosed, cave-like habitats with distinct environmental conditions, including darkness, restricted water flow, and vertical gradients in dissolved oxygen and particulate organic carbon. Compared to the external cover, interior communities showed reduced dominance of typical abundant North Sea hard-substrate taxa and increased heterogeneity, with higher contributions of sponges, calcareous tube worms, and brittle stars, resembling communities reported from marine cave environments elsewhere. Overall epifaunal cover was lower on the interior walls and broadly reflected vertical patterns in water quality. Organic matter accumulated on the interior seafloor, with indications of microbial mat formation. These findings suggest that the internal environmental conditions influence community development. Water replenishment hole design may therefore shape community composition inside monopiles, with implications for possible use as nature-inclusive design and environmental management.

1. Introduction

The rapid expansion of offshore wind energy introduces large areas of artificial hard substrate (AHS) to marine environments (Degraer et al., 2020; Glarou et al., 2020; Van Sluis et al., 2025). These structures are quickly colonised by diverse epifaunal communities, increasing local

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biomass and habitat complexity (Coolen et al., 2020; Zupan et al., 2024). As a result, offshore wind farm monopiles have become key sites for studying colonisation on man-made marine structures (Coolen et al., 2022; Degraer et al., 2020). Although distinct species zones establish with depth along the external surfaces of offshore structures (Krone et al., 2013), development of communities does not seem to reach a permanent climax situation over time (Zupan et al., 2023). The developing communities alter local ecosystem functioning, including food web structure and biogeochemical cycling (De Borger et al., 2021; Mavraki et al., 2020a). Understanding such patterns is increasingly important as offshore wind development reshapes coastal ecosystems, especially when introducing hard substrate in predominantly soft sediment habitats (Degraer et al., 2020).

New foundation features may further influence colonisation and thereby local biomass and diversity. An example of the last decade is the use of water replenishment holes (WRHs): openings in the submerged section of monopiles that allow passive exchange between internal and external seawater. WRHs and other larger openings have been integrated into North Sea monopiles in the Dutch North Sea since approximately 2019, with several wind farms (e.g., Borssele, Hollandse Kust Zuid and Hollandse Kust Noord) now employing this design feature. Their primary function is to mitigate the acidification of enclosed water and consequent risks of internal corrosion (Hilbert et al., 2011; Maher and Swain, 2018). Several studies have investigated the technical implementation of WRHs and the hydrodynamic processes governing water replenishment in monopiles, including internal water-level response and exchange velocities (Andersen, 2017; Carstensen, 2025; Carstensen et al., 2026; Jacobsen et al., 2025; Jacobsen and Lyng, 2024; Kesgin et al., 2024; Maher and Swain, 2018; Sarada et al., 2025; Tupkar and Sappe, 2022). In addition to corrosion prevention, the openings also allow organisms to access and colonise the previously isolated internal hard substrate, effectively creating a novel habitat within the monopile (Maher, 2018). As WRHs become increasingly common in foundation design, more monopile interiors are converted into accessible habitat for epifauna and other demersal, mobile species.

In contrast to external monopile surfaces, which are exposed to light, wave action, and strong tidal currents, monopile interiors represent semi-enclosed, dark environments. Within these environments, internal flow velocities can vary spatially and temporally depending on external hydrodynamic conditions and the size and number of WRHs (Jacobsen et al., 2025). Because replenishment is strongest near the WRHs, different parts of the monopile experience different exchange rates with the surrounding sea. This can create gradients in oxygen availability, food supply, and hydrodynamic conditions throughout the monopile interior. Despite increased application of WRHs, the ecological development within such man-made semi-enclosed habitats remains unknown and thus represents a critical knowledge gap in assessing the ecological impacts of offshore wind infrastructure. Studying hydrodynamics, water quality, and colonisation is highly relevant for understanding how WRHs influence biodiversity and ecosystem functioning. These insights can inform the development of offshore infrastructure design features that either enhance or mitigate ecological impacts, which is becoming increasingly relevant in offshore wind farm planning and tendering (Rijksoverheid, 2022; Ter Hofstede et al., 2023) and international nature-positive ambitions (World Economic Forum, 2025).

This study characterises the epifaunal community developing on the interior walls of WRH-equipped monopiles and determines how internal environmental conditions and vertical gradients shape this community. We (1) used video footage to compare epifaunal percentage cover inside and outside monopiles along a vertical gradient two years after construction and to obtain an impression of the seafloor and (2) modelled vertical patterns in particulate organic carbon (POC) and dissolved oxygen (DO) concentrations inside a monopile over one year. Based on the altered environmental circumstances inside the monopiles, we hypothesised that (1) epifaunal communities would differ between the interior and exterior of monopiles, with depth-related variation in species cover, and that (2) the limited water exchange through the water replenishment holes would result in vertical gradients in POC and DO within the monopile interior.

2. Materials & methods

2.1. Site description

This study was conducted in the offshore wind farm Hollandse Kust Zuid (HKZ), located at a minimum distance of 18 km from the Dutch coast (Fig. 1). The dominant sediment type in this region is sand, with large and medium sand dunes moving through the area (Netherlands Enterprise Agency (RVO), 2016). The water column is influenced by freshwater input from the Rhine, which can produce salinity stratification, while thermal stratification is negligible (Van Duren et al., 2021). The four monopiles investigated in this study (D1, E5, F1 and F4) are all located in the northwestern part of the wind farm (Fig. 1). The smallest distance between the individual monopiles is 2.8 km (D1 and F1), while the largest distance (D1 and E5) is 8.9 km (Rijkswaterstaat and Deltares, 2024). They were installed between September 2021 and April 2022 and are situated at depths from −23.26 m to −25.24 m (Table 1). The scour protection layer (SPL) was installed prior to monopile placement, resulting in identical material and grading on the interior and exterior seafloor.

2.2. Water replenishment holes

Each monopile consists of a hollow steel cylinder with a diameter of approximately 7 m, corresponding to an internal free-surface area of approximately 38.5 m^2. The height of the cylinder underwater depends on the local water depth at each monopile (Table 1). Four elliptical WRHs of 0.96 m height and 0.32 m width are located in the monopile wall and open directly into the hollow interior of the monopile. Each WRH has an opening area of approximately 0.24 m^2, resulting in a total WRH opening area of approximately 0.96 m^2 per monopile, equivalent to about 2.5 % of the internal free-surface area. This ratio is an important parameter governing water replenishment processes because it influences the relationship between exchange fluxes through the WRHs and the resulting internal water-level response. The positions of the holes were adapted for each monopile, so that two are located at an average height of 4.35 m above the seabed and two 1 m below the water surface (lowest astronomical tide, LAT). The upper WRHs have a fixed orientation of 191°N and 255°N. The lower WRHs were oriented at 191°N and 258°N for most investigated monopiles, except for monopile F1, which had the lower WRHs oriented at 191°N and 25°N (Table 1).

2.3. Biotic and abiotic field measurements

Several environmental parameters were measured on the outside (4 November 2024) and inside of monopile F1 (16 October 2024). Measurements collected outside the monopile were used to characterise ambient conditions and derive model boundary conditions, while measurements inside the monopile were used to assess internal environmental gradients and evaluate model behaviour. Two Eureka Manta 35+ multiprobes equipped with sensors for DO, chlorophyll-a, turbidity, temperature, pH, conductivity, and depth were used with a 0.5 Hz sampling interval. At three different depths, parameters were monitored for 15 min to allow measurement stabilisation. The last 5 min were averaged and used for further analysis. Abiotic data are shown in Fig. 2 and provided in Supplementary Data 2.

Vertical transect video recordings of the exterior monopile surfaces were collected between 30 August and 9 September 2024 (Table 1) using a remotely operated vehicle (ROV, Saab Seaeye Falcon®), around neap tide conditions to ensure stable operation and consistent image quality. A forward-facing camera (GoPro Hero 11) was mounted on the ROV at a slight downward angle, recording at 59.94 fps and with “wide view”.

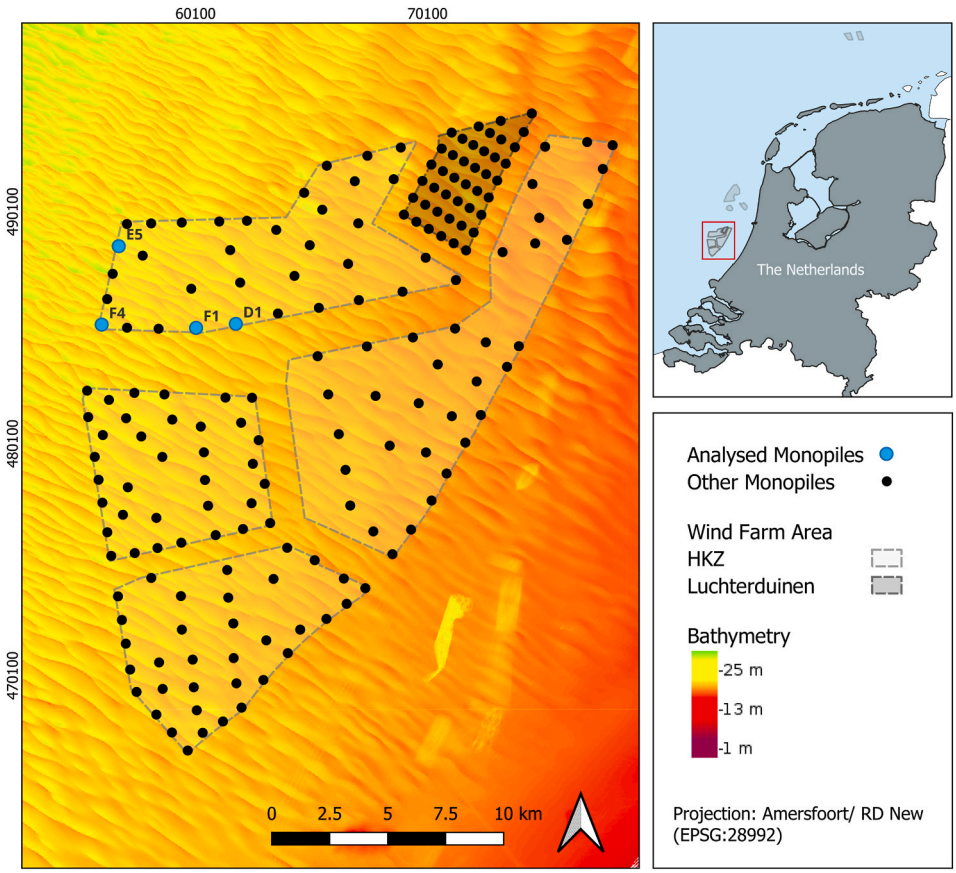

Fig. 1. Map of the offshore wind farm Hollandse Kust Zuid relative to the Dutch coast and highlighting monopiles D1, E5, F1, and F4 (Global Administrative Areas, 2025; Rijkswaterstaat, 2024; Rijkswaterstaat and Deltares, 2024). Created in QGIS 3.4.11.

Table 1
Technical background and monitoring information for the four investigated monopiles. Technical details include water depth at the seabed (mLAT), orientation and depth of the water replenishment holes (WRHs), installation date of the scour protection layer (SPL). Monitoring details include monitoring dates for the abiotic and biotic monitoring (video transects) of the interior and exterior of the monopiles, as well as number of video transects collected and frames analysed.

Monopile	Position	Water depth (mLAT)	Lower WRH orientation (°N)	Lower WRH elevation (mLAT)	Upper WRH orientation (°N)	SPL installation date	MP installation date	Abiotic monitoring date	Biotic monitoring date	# of transects	# of frames
E5	Exterior	−25.24	191, 258	−20.89	191, 255	1 Jul 2021	3 Nov 2021	-	2 Sep 2024	2	40
	Interior								9 Sep 2024	4	77
D1	Exterior	−23.26	191, 258	−18.91	191, 255	24 Jun 2021	1 Sep 2021	-	2 Sep 2024	2	43
	Interior								5 Sep 2024	4	87
F1	Exterior	−24.53	191, 25	−20.18	191, 255	14 Aug 2021	8 Sep 2021	4 Nov 2024	2 Sep 2024	2	30
	Interior							16 Oct 2024	6 Sep 2024	4	53
F4	Exterior	−24.97	191, 258	−20.62	191, 255	1 Jul 2021	21 Apr 2022	-	30 Aug 2024	3	44
	Interior								7 Sep 2024	4	100

Two parallel laser pointers spaced 27.5 cm apart were used to estimate the surface area visible in the recordings. Interior recordings were collected using a mini-ROV (VideoRay Pro 4) equipped with the same camera setup (GoPro Hero 11, same settings). Laser scaling devices were not available on the mini-ROV, preventing estimation of the visible surface area in individual still frames. Nine exterior and sixteen interior transects were recorded (Table 1). In addition to vertical transects, seafloor footage was also collected using the same ROV systems. These recordings were used to qualitatively assess seabed composition and organic matter accumulation on the interior and exterior of the monopile. Recordings and selected frames are available online under https://doi.org/10.5281/zenodo.20508299.

2.4. Video analysis

2.4.1. Frame selection

For each vertical transect, approximately one frame per depth meter was manually selected from the recorded footage when image quality was sufficient for taxonomic identification. In total, 317 interior frames and 157 exterior frames were analysed (Table 1). Due to the different natural light conditions, the overall quality of the interior frames was generally lower. Therefore, frames closer to the wall needed to be chosen to provide the best image quality, which resulted in smaller surface areas analysed for the interior frames.

2.4.2. Taxonomic classification and percentage cover

For each frame, a rectangular area of interest (AOI) was defined only including image regions with sufficient quality for taxonomic

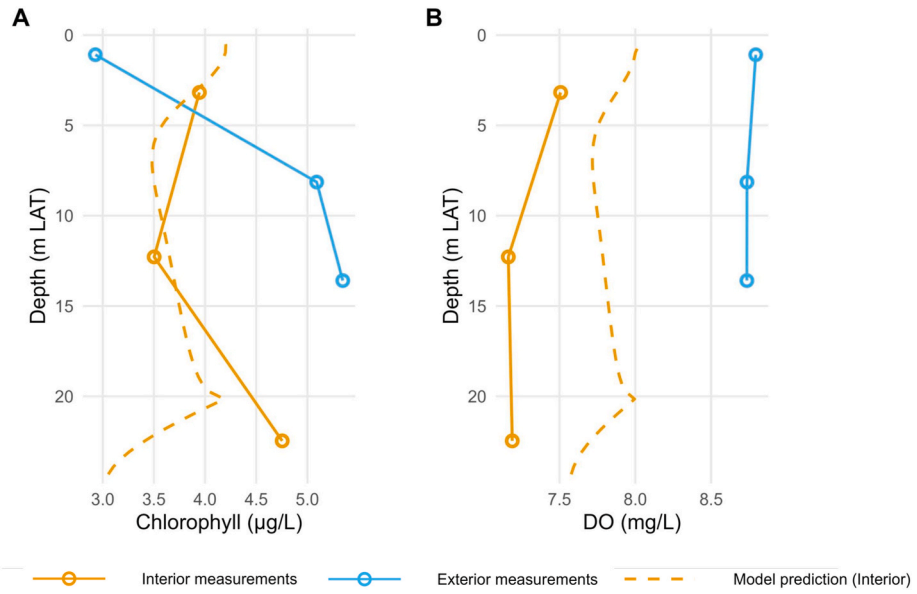

Fig. 2. Measured interior (orange) and exterior (blue) A) dissolved oxygen concentration (mg/L) and B) chlorophyll *a* concentrations (µg/L) during the monitoring campaigns on 16 October 2024 (interior) and 4 November 2024 (exterior). Model predictions for both parameters at 12:00 on 16 October 2024 are indicated by the orange dashed lines. Chlorophyll *a* concentrations were modelled via conversion from POC concentrations.

identification, excluding blurred regions and water. The AOI dimensions were estimated using camera geometry and available scale references. For exterior images, the laser scale was used as a reference, whereas for interior images, organism dimensions within the images were used as object-scale references. The horizontal field of view of the camera (109°) and the estimated width of the upper image edge, obtained from the corresponding scale reference, were used to calculate the camera-to-wall distance. The vertical field of view was derived from the camera aspect ratio (16:9). The estimated horizontal and vertical camera angles were then incorporated into the geometric calculation to determine the visible wall surface area and define the AOI.

A point grid (200 points/m^2) was overlaid using TransectMeasure (SeaGIS-V4.23) and AOI size included as covariate (section 2.5) to account for the differences in AOI between frames (Fig. S1). Each point was classified as the lowest identifiable taxonomic group where possible. Points containing only bare substrate or biofilm were classified as "not colonised", whereas points that could not be identified because of local image quality were classified as "blurry". Blurry points (10.5 % of the total) were excluded from further analysis.

The percentage cover per taxon was calculated for each frame based on the remaining points. The average percentage cover per taxonomic group per depth was calculated across transects inside and outside for each monopile.

2.4.3. *Biomass estimation*

To derive biomass estimates along the depth gradient for use in the water-quality model, a semi-quantitative approach was applied to the frames of monopile F1. Frames were first visually ranked within each transect from lowest to highest biomass. Individual organisms were counted in lowest and highest biomass frames and converted to AFDW using species-specific mean individual weights from published and internal laboratory datasets from hard-substrate communities in the southern North Sea and, where required, the Wadden Sea (Dannheim et al., 2025a; Wageningen Marine Research Den Helder, unpublished data). Linear interpolation between ranked frames was then used to assign AFDW values to all remaining frames along each transect.

2.5. *Generalised linear latent variable models (GLLVMs)*

To statistically test differences in species cover along the depth gradient between the interior and exterior of monopiles, generalised linear latent variable models (GLLVMs) were created using the gllvm package (Niku et al., 2019; Van der Veen, 2025). GLLVMs provide statistical testing of relations between multiple environmental variables and multiple species simultaneously. Model preparation followed Zuur and Ieno (2025) and Van der Veen (2025). Only species with a minimum of 15 presence observations in the full dataset were included in the model.

Model formulation took the form of a polynomial regression with quadratic and cubic terms for depth, in interaction with a factor variable inside versus outside, to account for differences in depth patterns. The estimated AOI of each frame was included to account for differences in area analysed (Fig. S1). Variation in AOI may influence taxonomic observations because larger analysed areas increase the probability of detecting rare taxa while potentially reducing image resolution and the level of taxonomic identification that can be achieved. Including AOI as a covariate accounted for potential differences in detection and classification associated with variation in analysed area. The inclusion of a parameter on the modelled oxygen concentration was considered, but both mean and minimum oxygen concentration were highly collinear with depth (Fig. S3). Therefore, only depth was included, as depth-related patterns on the outside of monopiles have been reported multiple times (Coolen et al., 2022; Dannheim et al., 2025b; Krone et al., 2013), while on the interior it captures the combined effects of vertical stratification and increasing vertical distance from the nearest water replenishment hole on water quality in a consistently measured variable.

Latent variables were included to account for relations with unknown environmental variables not incorporated in the model. To test whether latent variables were essential, models with 0, 1 and 2 latent variables (*jitter.var* set to 0.1, with 25 initial runs per model) were created and compared using the Akaike Information Criterion (AIC) (Akaike, 1973). The model with 2 LV had the lowest AIC and was used to present further results. Video transect ID nested in turbine ID was included as a random effect to compensate for dependency between observations caused by repeated sampling of the same monopile. Large numbers of zero observations were present in the data of most species. Therefore, the data were assumed to be zero-inflated, and a beta hurdle distribution (betaH) was applied (Korhonen et al., 2024), using the extended variational approximations (EVA) approach (Korhonen, 2025; Korhonen et al., 2023).

Model validation was performed by plotting randomised quantile (Dunn-Smyth) residuals against fitted values, variables included in the model, and fitted vs observed values, inspecting the plots visually to confirm if assumptions of homogeneity of variance and normality were met. Generalised species pattern plots to visualise differences between the interior and exterior of monopiles along the depth gradient were created using data from the predict.gllvm function. For prediction purposes, the estimated AOI was set to the average in the complete dataset. Model output is available in Supplementary Data 4.

All statistical analyses were carried out using R (R Core Team, 2025) in RStudio (version 2024.04.2 Build 764; Posit Team, 2025). Visualisations were done using the ggplot2 package (Wickham, 2016).

2.6. Numerical modelling framework

Abiotic conditions inside offshore wind monopile foundations equipped with WRHs were quantified using a coupled numerical modelling framework. The framework combined a hydrodynamic model that translated external metocean forcing into exchange fluxes through WRHs with a one-dimensional vertical (1DV) water quality model that simulated internal distributions of DO and POC.

2.6.1. Hydrodynamic water replenishment model

Water exchange between the ambient sea and monopile interior was simulated using a Deltares in-house one-dimensional vertical (1DV) hydrodynamic replenishment model representing the monopile as a vertical water column beneath a compressible air pocket. Exchange occurs through WRHs at prescribed elevations, while horizontal variability is neglected and cross-sections are assumed well mixed.

Inflow and outflow through the WRHs are driven by time-varying pressure differences resulting from water-level fluctuations, wave-induced dynamic pressures, and current-induced pressures around the monopile circumference. Air trapped above the internal water column can escape through ventilation openings, while compression and expansion of the enclosed air volume provide additional damping of internal water-level oscillations. The flow through each WRH is computed using an unsteady Bernoulli formulation with hydraulic loss coefficients representing contraction, expansion, and jet losses. When the local external water level falls below the elevation of a WRH, the wave-induced external pressure contribution at that opening is set to zero. This prevents artificial suction during wave troughs; exchange through that opening only occurs when it is hydraulically connected to the surrounding water.

The model was applied to the HKZ monopiles using as-built geometries and WRH configurations. Hourly metocean forcing was prescribed using spectral wave parameters from a regional SWAN model and water levels and depth-averaged currents from the Dutch Continental Shelf Model (Deltares, 2022). Wave-induced pressures were derived using linear wave theory applied to stochastic JONSWAP spectra, with water-level and current-induced pressures added through linear superposition. The resulting exchange fluxes form the hydrodynamic input to the water quality model.

The hydrodynamic replenishment model was verified against laboratory wave experiments and calibrated loss coefficients, reproducing internal water-level oscillations and exchange fluxes within approximately 10 %, indicating that the dominant replenishment processes are adequately represented.

2.6.2. Water quality model

Internal water quality was simulated using the open-source DELWAQ model (Deltares, 2026; Postma et al., 2003) in a 1DV configuration. The monopile interior was discretised into 61 vertical layers with variable thickness reflecting the tapered geometry. Horizontal gradients were neglected. Exchange fluxes from the hydrodynamic model were imposed as advective transports between layers. Layers above the upper WRH were allowed to adjust dynamically with internal water-level variations, while layers below the lower WRH experienced recirculation driven by inflow and outflow at that elevation.

Two state variables were modelled as primary indicators of habitat suitability: dissolved oxygen (DO) and particulate organic carbon (POC). In this study, water quality refers specifically to these two variables, which were used as proxies for oxygen availability and food availability, respectively. The model includes vertical advection and diffusion, POC sedimentation, microbial decomposition of organic matter, and biotic consumption of oxygen and POC. Ambient DO and POC concentrations were prescribed as boundary conditions for inflowing water. Oxygen concentrations were assumed constant and representative of offshore North Sea conditions (8.0 mg/L). Ambient POC concentrations (0.42 mg/L) were estimated from measured chlorophyll *a* concentrations outside the monopiles using a fixed POC:Chl *a* mass ratio of 100:1 (equivalent to 0.1 mg POC/L per µg Chl *a*/L), which is within the range reported for the region (Van Der Zee and Chou, 2005). Initial internal concentrations were set equal to ambient values.

Biotic consumption was parameterised using literature-based ecophysiological rates combined with observed biomass distributions. Oxygen consumption rate (OCR in µmol O_2 g $AFDW^{-1}$ h^{-1}) and carbon assimilation expressed as POC in µg C assimilation µg C^{-1} of biomass m^{-1} day^{-1} were compiled for hard substrate species. The observed species on the inside of monopile F1 were used as a representative group for the location. Where the video analysis identified higher order taxonomic groups, location-representative species for which relevant ecophysiological information was available were chosen (e.g. *Jassa herdmani* for Amphipoda).

Estimates of biomass were derived from the video footage. Conversion of OCR and carbon assimilation to AFDW was undertaken using conversion factors (Ricciardi and Bourget, 1998). Limited literature was available on biomass to organic carbon content conversion, especially for relevant individual species. Commonly used ranges in literature vary between 40 and 50 % (Kindeberg et al., 2024; Mackinson and Daskalov, 2007; Rueda et al., 2005; Wijsman et al., 1999). Therefore, the carbon content of the biomass (g AFDW m^{-2}) was determined using a conversion factor of 0.5 (Kindeberg et al., 2024) and subsequently applied to estimate the carbon assimilation rates of relevant species as input for the model.

Literature data on oxygen consumption rates (OCR) were available for 10 of the 25 taxa observed in monopile F1, while POC assimilation rates were available for four of these taxa (Harrington, 2010; Kumala et al., 2023; Mavraki et al., 2020b; Migné and Davoult, 1997; Noisette et al., 2016; Ortega et al., 1988; Pack et al., 2021; Souster et al., 2018; Voet et al., 2022). Seasonal variability was disregarded due to limited data availability. Mean OCR and POC assimilation rates were subsequently calculated from the available values and applied to represent the community composition observed in each video frame.

Model performance was evaluated against in situ interior measurements collected during the monitoring campaign of 16 October 2024 (Fig. 2). The model reproduced the observed order of magnitude and general vertical structure of internal concentrations, including elevated values near WRH elevations and reduced concentrations in poorly flushed zones. Deviations between modelled and measured concentrations were attributed primarily to simplified boundary conditions and uncertainty in biomass-derived consumption rates. Given the limited validation dataset and the use of constant ambient boundary conditions, the model should primarily be interpreted as a first-order tool for exploring replenishment-driven patterns and differences between monopile configurations rather than for predicting exact concentration levels or short-term concentration dynamics.

3. Results

3.1. Community composition and cover patterns

In total, 28 taxa, comprising 9 phyla, were identified. Differences in

community composition were observed between interior and exterior monopile surfaces as well as along the vertical gradient.

While exterior surfaces were almost completely colonised (97.4 ± 4.3 %, indicated as mean cover ± standard deviation in this section), the interior walls exhibited more bare area (84.4 ± 15.1 %). The total cover on the interior of the monopiles was generally higher near the water surface and seafloor and lower in middle range depths (around 8-16 m; Fig. 3).

On the exterior of the monopiles, mats assumed to be built by Amphipoda (sessile Malacostraca), anemones (Hexacorallia), Bivalvia, and colonial Ascidiacea were dominant, collectively accounting for an average of 78.1 ± 12.9 % of the total cover. Bivalvia were particularly dominant between 0 and 8 m on monopiles F1 and D1, but this zone was restricted to 0-4 m for monopiles F4 and E5. Most Bivalvia were blue mussels (*Mytilus edulis*), however, on monopile F4, the non-indigenous Pacific oysters (*Magallana gigas*) dominated. Below the Bivalvia-dominated zones, Amphipoda became more prevalent, combined with varying covers of different Hexacorallia species and colonial Ascidiacea (mainly *Diplosoma listerianum* species complex).

On the interior walls, Bivalvia were largely absent. *M. edulis* occurred only in the immediate vicinity of the upper WRHs and *M. gigas* were observed sporadically. Similar to the communities in the deeper parts of

Fig. 3. Mean percentage cover of the exterior and interior of monopiles D1, E5, F1, and F4 per taxonomic category for different depths. * indicates the vertical position of the water replenishment holes. Category 'Other species' includes unidentified species, *Alcyonium digitatum*, and Ulva spp. (the latter with two observations). Underlying data is available in Supplementary Data 3.

the exterior of the monopiles, the communities on the interior consisted of Amphipoda mats, colonial Ascidiacea, and different Hexacorallia species, but these dominant exterior species had lower cover on the interior (54.6 ± 23.0 %). Layer thickness (not measured) of these species also appeared to be much lower on the interior walls. In contrast to the exterior, additional taxonomic groups reached higher cover percentages on the interior, including Porifera (Demospongiae), brittle stars (Ophiuroidea), and Serpulidae (Polychaetae). Specifically, Serpulidae consistently covered a large part of the walls, with the highest cover (up to 39 %) at intermediate depths. Ophiuroidea were exclusively observed on the interior of the monopiles. The non-indigenous slipper limpet (*Crepidula fornicata*, Gastropoda) had a lower average cover on the interior (0.7 ± 1.9 %) compared to the exterior (1.5 ± 2.8 %).

Differences between monopiles were also evident on the interior walls. On the interior of D1 and F1, no Ophiuroidea were observed. Colonial Ascidiacea covered less area on the interior of F1 and F4. The overall area covered by epifauna on the interior of monopile D1 was higher than for the other monopiles. Porifera were particularly prevalent in monopile E5. These observed differences were further examined using species-environment models.

3.2. Species-environment relationships

The predicted taxa-specific trends between interior and exterior surfaces as well as along the depth gradient were assessed using the GLLVM (Fig. 4). Significant differences (all reported when $P < 0.05$) in observed cover percentage between the interior and exterior of the monopiles were present in four taxa (Supplementary Data 4). Colonial Ascidiacea and Serpulidae percentages were significantly higher on the interior than on the exterior, while *M. edulis* and Amphipoda percentages were significantly lower on the interior than on the exterior.

In addition to the percentages, taxa presence likelihood (predicted within the hurdle part of the model) of *Sagartia undata* was significantly lower on the exterior than on the interior, while likelihood of *Metridium senile*, *C. fornicata*, *Cylista elegans* and *Urticina* sp. was significantly lower on the interior than on the exterior.

Depth patterns could be visualised for a number of taxa (Fig. 4). Significant differences in percentage cover were observed in 4 out of the 19 taxa for the linear depth-cover relation, 5 for the quadratic term and 6 for the cubic term. *M. edulis* was most abundant in shallow parts of the exterior walls, a pattern significantly different from the interior. In deeper sections, the species showed low percentages on both the interior and exterior. Amphipoda had similar cover percentages on the interior and exterior at shallow depth, but at depths from mid-water to near-seabed, percentage cover was significantly lower on the interior than on the exterior. Colonial Ascidiacea showed a significant depth-related pattern, with the highest cover percentages in shallow to mid-water sections of the interior of the monopile and with lower percentage cover on the exterior. Serpulidae, while near-absent on the exterior, showed increasing percentages with depth on the interior. *M. senile* showed opposing patterns on the interior vs the exterior, with high densities in shallow water on the interior, reducing with increasing depth.

3.3. Organic matter accumulation

In addition to the vertical patterns, clear differences in seafloor structure were observed between the interior and exterior of the monopiles. The seafloor on the interior was largely covered by soft material, present on top of the scour protection layer (Fig. 5). The distribution of rocks and soft substrate was patchy. Grey layers on the seafloor, interpreted as microbial mats forming under hypoxic conditions, were present on the interior of all four monopiles. In contrast, exterior recordings showed that the original rock substrate was not covered by sediment or loose organic matter, with only spaces in between rocks filled with sediment and no microbial mats.

3.4. Modelled environmental conditions

The numerical model simulated the spatial and temporal variability of DO and POC on the interior of the monopiles (Fig. 6). Both variables exhibited a pronounced vertical structure. Along the vertical profile, concentrations were elevated in the vicinity of the WRHs and reduced in zones above, below and between the WRHs. This vertical gradient reflects differences in replenishment efficiency, as exchange with ambient seawater is strongest near the openings and weaker in more isolated parts of the water column. The clear temporal variability follows temporal changes in external hydrodynamic forcing. Periods with increased wave activity and stronger currents correspond to enhanced water exchange through the WRHs and lead to higher internal DO and POC levels and reduced vertical gradients. Conversely, during calmer periods, replenishment was weaker and vertical gradients became more pronounced, particularly in the lower part of the monopile. These patterns indicate that internal environmental conditions are strongly controlled by external forcing, with waves playing a key role in short-term variability and seasonal changes in exchange intensity.

Modelled mean concentrations of DO and POC were similar for monopiles D1, E5, and F4, which share the same WRH configuration (Fig. 7). Differences between these monopiles are minor and primarily related to variations in water depth, which slightly affect pressure forcing and internal volume. Monopile F1 showed higher mean concentrations and a reduced vertical gradient. Fig. 7C and D illustrate instantaneous modelled conditions on 20 March 2024 corresponding to the moment of maximum inter-monopile differences in DO and POC. In monopile F1, the lowest DO and POC concentrations occurred near the lower WRHs rather than between the upper and lower WRHs. Taken together, the model results demonstrate how WRH configuration and external hydrodynamic forcing influence replenishment patterns within monopiles. The differences between monopile configurations are consistently reflected in the simulated long-term DO and POC conditions, while Fig. 7C and D provide an illustrative example of the resulting instantaneous spatial distributions. The precise vertical concentration distributions should be interpreted with caution and primarily serve to illustrate replenishment-driven variability within the monopile.

4. Discussion

This study provides the first investigation of the water quality and epifaunal communities developing within the interior of offshore wind monopiles equipped with WRHs. The results demonstrate that within these monopiles, a specific semi-enclosed habitat develops with epifaunal communities distinct from the exterior walls. These communities differ in composition and total cover percentage over the water depth gradient.

Modelled DO and POC concentrations near the WRHs resembled the surrounding water masses and are reduced around mid-depth, between the WRHs, and below the lower and above the top WRHs. Patterns in the epifaunal community composition and total cover reflect these gradients, with the lowest cover in the mid-depth section on the interior walls. The interior communities also generally exhibited lower overall cover, reduced dominance of typical exterior taxa such as Amphipoda, Hexacorallia, and Bivalvia, and increased contributions from taxa such as Porifera, Serpulidae, and Ophiuroidea. A comparison of the four studied monopiles indicated differences in community composition among monopiles and that the orientation of the WRHs mattered for the interior water quality. Together, these findings suggest that internal environmental gradients may influence epifaunal community composition and that the implementation of WRHs creates a novel ecological habitat within offshore wind farms.

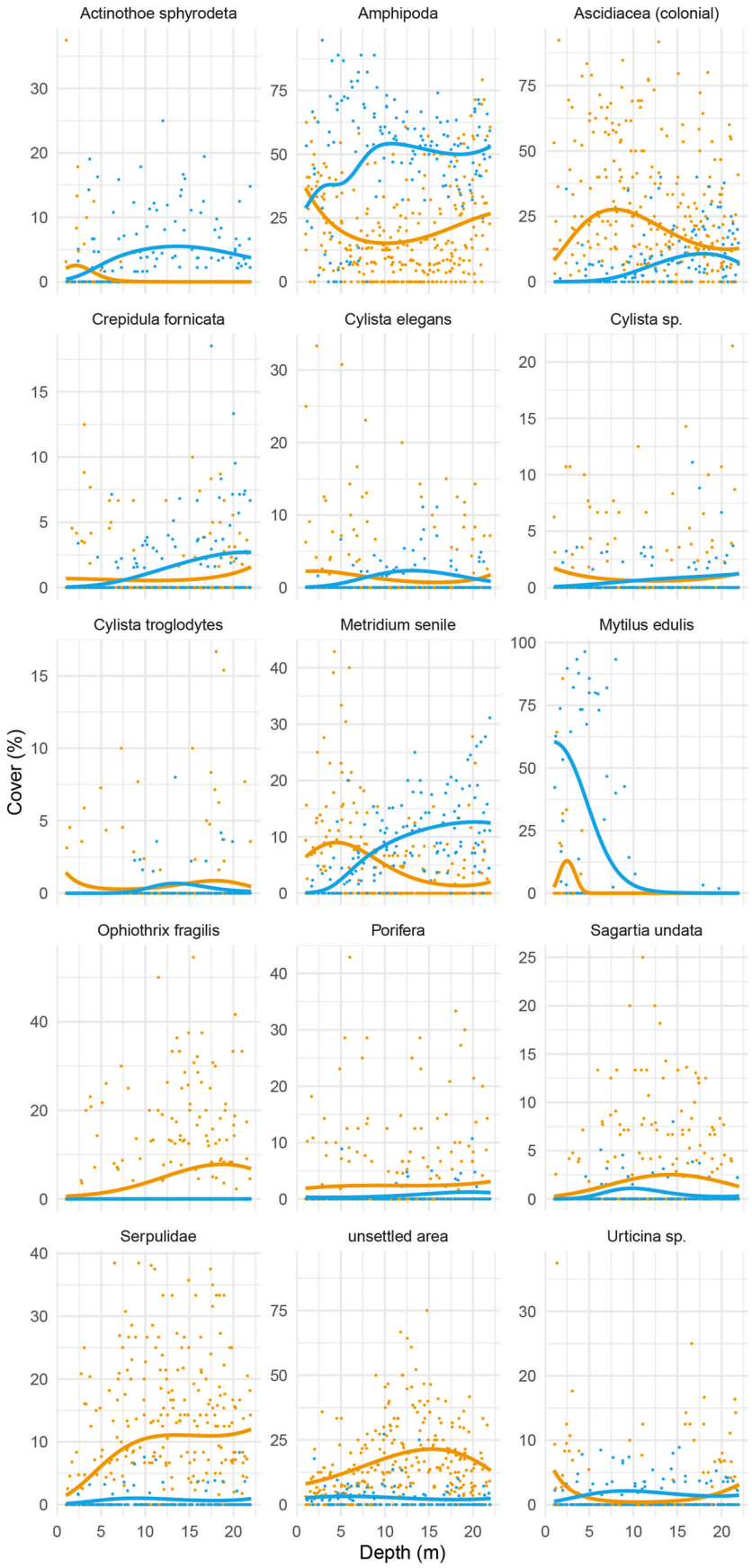

Fig. 4. Generalised linear latent variable model results per taxon for interior (orange lines) and exterior (blue lines) of the monopiles, along the depth gradient, with observed data (dots) from all four monopiles.

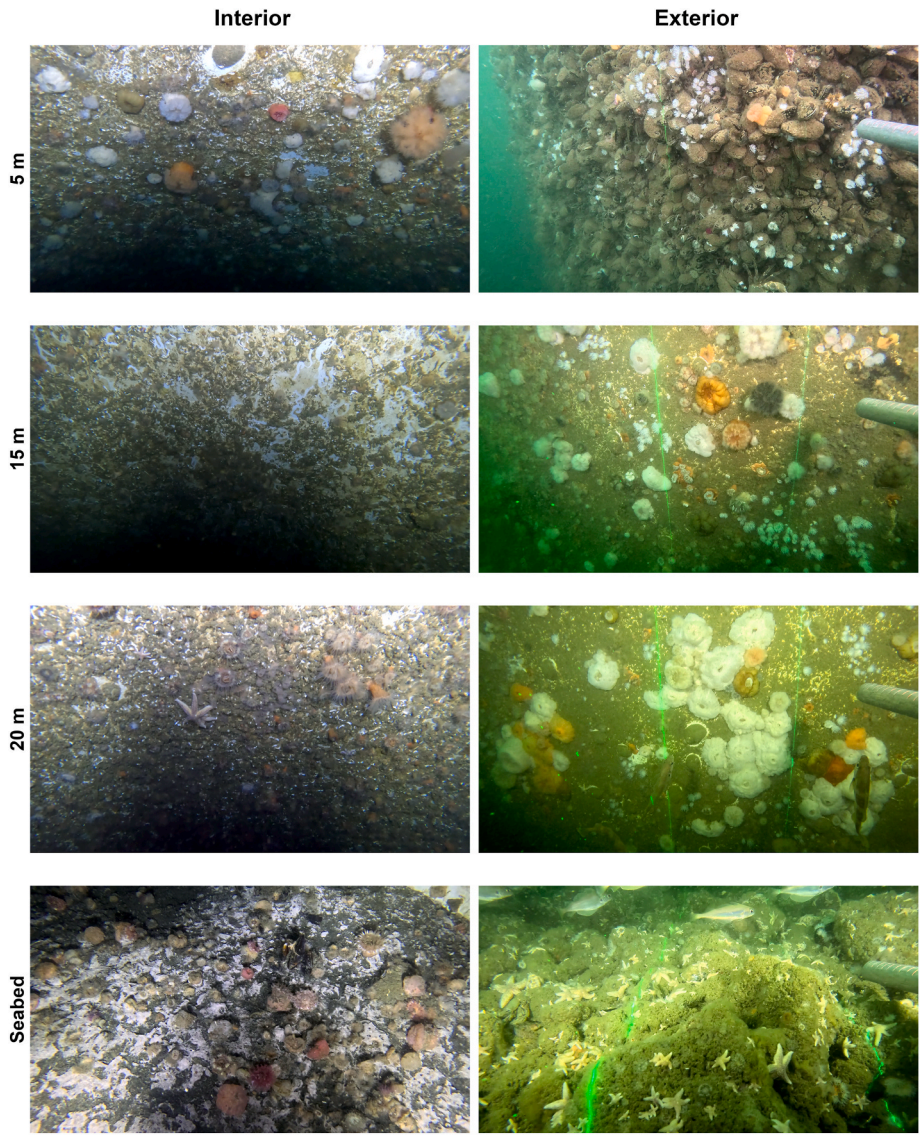

Fig. 5. Communities at different depths on the vertical walls and seabed on the interior and exterior of the monopiles. The visible amount of organic matter on the interior of the monopiles is higher than on the exterior. The grey layers likely are microbial mats forming under hypoxic conditions.

4.1. Exterior and interior communities

Artificial hard substrate in the southern North Sea typically shows depth-driven vertical zonation patterns in the epifaunal communities: a mussel-dominated layer in the upper 5 m, an Amphipoda-dominated mid-layer (*Jassa herdmani*, 5-15 m), and a layer of plumose anemone (*Metridium senile*) extending towards the seabed (Coolen et al., 2022; Krone et al., 2013). The communities on the exterior of the investigated monopiles broadly corresponded to these general patterns, with a Bivalvia-dominated shallow zone and Amphipoda and Hexacorallia present in deeper zones. However, we did not observe a clear distinction between Amphipoda- and Hexacorallia-dominated zones.

The interior walls exhibited different patterns. Specifically, the absence of Bivalvia except near WRHs, the increased presence of Porifera and Serpulidae, and new appearance of Ophiuroidea, which were not observed on the exterior walls, stand out. Increased presence of Serpulidae was also observed inside enclosed space in a shipwreck (Walker et al., 2007). Several mechanisms may explain the observed patterns in community composition and total cover, including environmental stress, species' interactions, and larval supply and settlement. The differences are consistent with the variation in environmental conditions between the interior and exterior as well as along the vertical axis. Reduced DO and POC, limited water flow, and constant darkness create environmental stress inside the monopile that may constrain taxa commonly found on AHS as well reducing overall cover. Although DO is only marginally reduced and still within normal limits, the reduction in flow speed and POC concentration are likely explainers for the observed community shift (Riisgård and Larsen, 2015; Wildish and Kristmanson, 1997). Exterior wall communities are likely shaped through an inhibitory response (Connell and Slatyer, 1977; Coolen et al., 2022), meaning that a diverse colonisation is prevented by early colonisers with strong competitive traits. *M. senile* and *Jassa* spp. are extremely successful colonisers as they prevent settlement of other species through e.g., occupying space, overgrowing or smothering recruits, and feeding on other species' larvae (Beermann, 2013; Nelson and Craig, 2011). In our observations, *M. senile* cover on the interior of the monopiles was highest near the water surface, contrasting with its typical increase toward the seabed on exterior walls. Although *M. senile* is highly tolerant to a large range of environmental conditions, including anoxia and a range of flow speeds and shows trophic plasticity (Mavraki et al., 2020c; Wahl, 1984), the present conditions may still affect them, as flow speeds have been shown to affect reproduction, morphology and prey capture (Anthony,

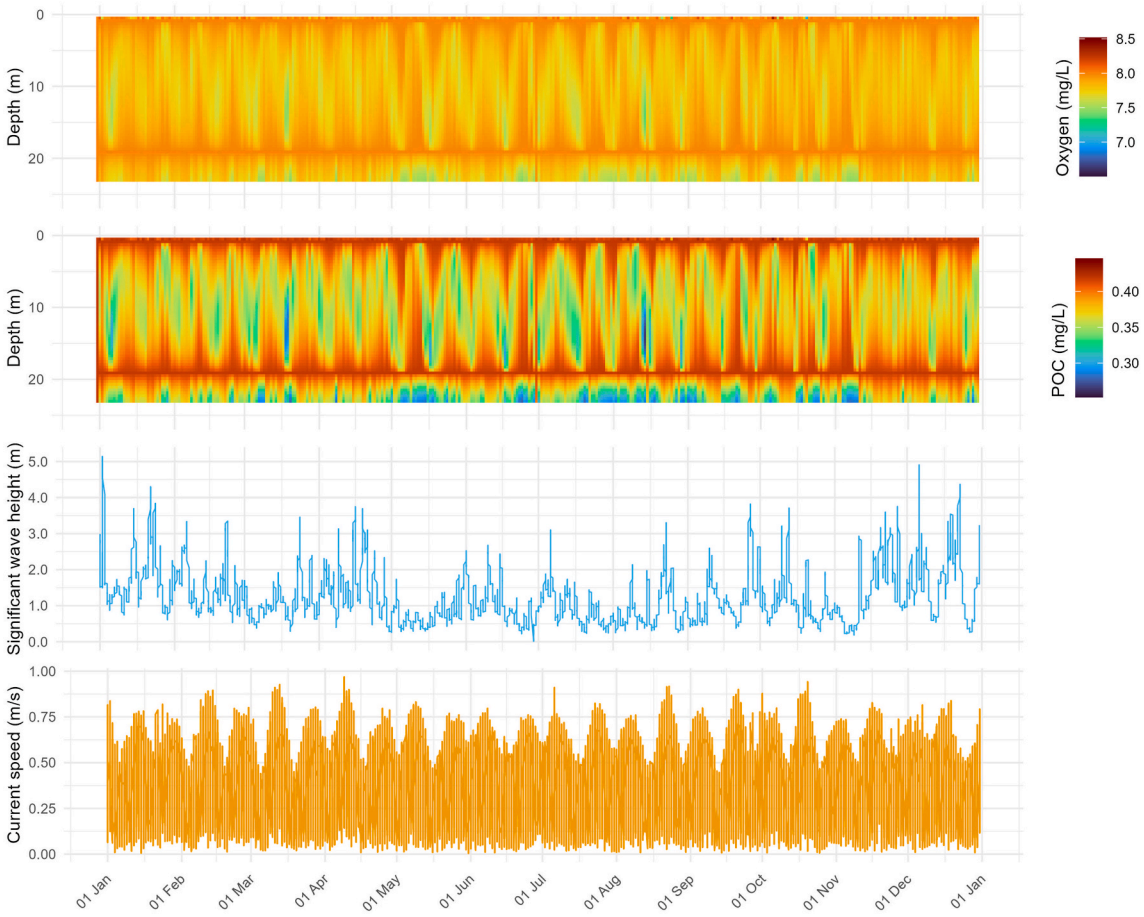

Fig. 6. Hourly modelled DO (top), POC (middle), and modelled hydrodynamic forcing conditions (bottom), exemplified by spectral wave height and absolute current velocity, for the F1 monopile for 2024.

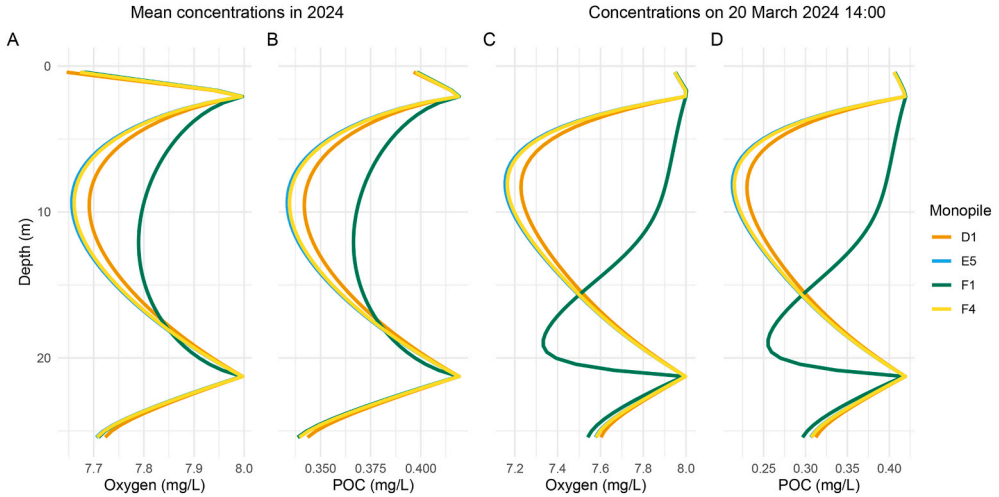

Fig. 7. Mean concentrations for 2024 of A: Dissolved oxygen (DO); B: Particulate organic carbon (POC). Concentrations on 20 March 2024 for C: DO and D: POC for the four different monopiles.

1997; Lesser et al., 1994). Amphipoda are sensitive to abiotic factors, such as DO, water movement, and sedimentation (Beermann and Franke, 2012; Conradi et al., 1997; Wu and Or, 2005). *Jassa* spp. generally show a preference for more exposed locations in the North Sea, potentially due to food availability and colonisation chances (Beermann and Franke, 2012). The reduced presence or competitive abilities of these species on the interior of the monopile, likely due to environmental stress, potentially alleviates competitive pressure, allowing other species to settle. However, some taxa observed with lower percentages on the outside, such as Serpulidae, may be equally present but obscured by overgrowth, leading to underrepresentation in video-based assessments. The exclusive observation of Ophiuroidea, likely dominated by *Ophiothrix fragilis*, on the interior walls of the monopiles warrants further consideration. *O. fragilis* is primarily a

suspension-feeder associated with current-exposed habitats in open waters (Hughes, 1998). Its occurrence inside monopiles is therefore unexpected due to suspected low flow speeds. However, feeding activity is optimized under moderate rather than extreme flow conditions (Davoult and Gounin, 1995). The interior of monopiles E5 and F4 may provide localised hydrodynamic conditions with intermediate flow speeds and suitable turbulence that favour suspension feeding. A further explanation is the naturally patchy distribution of *O. fragilis*. Brittle-star aggregations are highly discontinuous and may be maintained partly through responses to conspecific individuals rather than environmental conditions alone (Broom, 1975). The limited occurrence of Ophiuroidea patches on monopile walls may therefore reflect their aggregated behaviour and dependence on established individuals. Warner (1971) also reported contrasting distributions between *O. fragilis* and *M. senile*, consistent with the pattern observed here and potentially reflect differences in environmental preferences or species interactions. The co-occurrence of Ophiuroidea and Porifera corresponds to what is known from other locations and potentially reflects juvenile refuge formation or trophic facilitation (Oliveira et al., 2024; Turon et al., 2000).

Larval supply, dispersal, and behaviour further contribute to differences between interior and exterior communities. Slower colonisation and low total cover on the interior is likely driven by the limited flow and exchange of water, which strongly reduces the supply of settlement-competent larvae, combined with predation on these by the already established filter feeders (Palardy and Witman, 2014). This can be amplified by species specific characteristics in settlement. For instance, *Jassa* spp. lack planktonic larvae and rely on drifting individuals for dispersal (Havermans et al., 2007). Restricted water exchange may limit their colonisation success and explain their reduced presence on the interior walls. Many benthic organisms, including Amphipoda, *M. senile*, and Ascidiacea are capable of photoreception in their larval and adult stages and show behavioural responses to light stimuli (Kusakabe and Tsuda, 2007; Lynn et al., 2024; Navarro-Barranco and Hughes, 2015). *D. listerianum* larvae for instance prefer dim light just before settlement (Crisp and Ghobashy, 1971), meaning that individual behavioural patterns may affect settlement and survival success under these unique conditions, and thus contribute to the increased cover by Ascidiacea on the interior walls.

The interior conditions - restricted hydrodynamics, POC gradients, and absence of light - create conditions resembling marine caves, which are also characterised by distinct communities dominated by e.g., Porifera, Bryozoa, calcareous tube worms, or Ascidiacea (Gerovasileiou and Voultsiadou, 2012; Readman et al., 2024). Like marine caves, the monopile interiors exhibited small-scale patchiness (Denitto et al., 2007; Martí et al., 2004). The lower overall cover observed may correspond to slow colonisation and the community development known from marine caves (Denitto et al., 2007; Navarro-Barranco et al., 2015). Although monopile interiors differ from natural caves in their smooth steel surfaces, lower structural complexity, and younger substrate age, the shared environmental conditions suggest that they may nevertheless function as analogous semi-enclosed habitats.

4.2. Variability between monopiles

Despite the clear patterns in some species and total cover, substantial variability in community composition was observed between monopiles, particularly on the interior walls. Variation on the interior walls may partly be explained by the differences in water quality due to the WRH configuration. However, because only F1 had a different WRH configuration, additional factors must contribute to the observed differences. Variation on the exterior walls was also evident, including the dominance of *M. gigas* on monopile F4. Small-scale environmental variations are likely contributors, as even limited distances can influence colonisation and community composition (Rule and Smith, 2005; Zintzen et al., 2008). Furthermore, the monopiles were installed in different seasons (Table 1). Most observed North Sea taxa exhibit seasonal recruitment. For instance, *M. edulis, M. gigas, and O. fragilis* recruitment typically peaks in summer and early autumn (De Vooys, 1999; MacBride, 1907; Morgan and Jangoux, 2002; Teixeira Alves et al., 2021), while barnacle recruitment may start in spring (e.g., *Balanus crenatus*; Rainbow, 1984). Variation in the timing of monopile placement may thus result in differences in total cover and diverging community trajectories due to variability in larval supply and early recruitment processes (Underwood and Chapman, 2006).

4.3. Ecological risks and benefits

The observed patterns have important implications for potential benefits as well as risks associated with the implementation of WRHs. The development of a novel artificial habitat with distinct communities raises questions regarding its role in the stepping-stone effect and establishment of introduced non-indigenous species (iNIS, Tyrrell and Byers, 2007). In this study, the iNIS *C. fornicata, M. gigas*, and several cryptic Ascidiacea, not identified up to species level but likely iNIS as well, were found on the exterior and interior of the monopile. However, *C. fornicata* and *M. gigas* exhibited a lower cover on the interior than on the exterior of the monopile, suggesting that the internal habitat is less suitable for these species. In contrast, the colonial Ascidiacea were more abundant on the interior, particularly in the shallow-to mid-depth zones, suggesting that the novel habitat may support specific iNIS that profit from reduced competition or are adapted to the internal environmental conditions. Taxonomic uncertainty limits the evaluation of ecological risks on the new habitat. Molecular approaches including eDNA, could help with early detection of iNIS.

The videos revealed notable accumulation of organic matter on the interior seafloor, suggesting reduced export under the limited water exchange. The observed grey mats are likely microbial mats, similar to those documented in marine environments with limited water exchange and often high organic inputs, such as seasonally in Lake Grevelingen (The Netherlands), the Baltic Sea, marine caves, or the sediments underneath fish farms (Aranda et al., 2015; Gerovasileiou and Bianchi, 2021; Lipsewers et al., 2016; Noffke et al., 2016). The organic matter accumulation may increase microbial oxygen demand for degradation, which, together with the already lowered DO concentration predicted near the seabed (Fig. 6), can result in hypoxic conditions at the sediment-water interface (Hargrave et al., 2008). Although the model already predicts decreased DO concentrations near the seabed, they likely represent an upper estimate because sediment oxygen demand and other biogeochemical processes were not explicitly included in the model. Persistent low-oxygen conditions can promote the development of anaerobic microbial communities and sulphur-oxidizing bacterial mats, while reducing macrofaunal abundance and altering benthic ecosystem processes, potentially creating zones unsuitable for most aerobic benthic organisms and altering presence of mobile fish and crustaceans (Conley et al., 2009; Grünke et al., 2011; Hargrave et al., 2008; Levin et al., 2009). A 16S rRNA gene analysis could identify the dominant taxa and better assess the ecological and biogeochemical implications of these communities (Lemoinne et al., 2024; Van der Loos and Nijland, 2021). It is currently unclear, whether these conditions on the seafloor are seasonal or also remain during months with higher wave activity and consequent water exchange. Future monitoring should therefore investigate the temporal persistence and severity of the low-oxygen conditions on the interior seabed.

The installation of monopiles with WRHs approximately doubles the available vertical hard substrate in wind farms. Due to limited data on biomass, it remains unclear whether the biomass associated with interior communities represents a meaningful increase in total epifaunal biomass. This uncertainty limits possibilities to predict the magnitude of effects on biogeochemical processes and benthopelagic coupling.

The additional epifauna may also further enhance feeding opportunities and attract fish, while the interior could also function as shelter for

species that utilise three-dimensional or sheltered spaces as habitat. If optimized with the goal of not only reducing acidification but also to provide a meaningful increase of an asset of biodiversity of the wind farm, WRHs may function as a creative nature-inclusive design (Degraer et al., 2026) that enhance natural values beyond the natural local environment. Adjustments in number, orientation, or size may induce changes in habitat suitability and alter the epifaunal community as well as the potential for mobile species to use the interior as a shelter. The potential of using monopile interiors by fish and other mobile species remains unclear and warrants further investigation. Accessibility of the habitat to predatory species such as seals should also be considered.

The implementation of WRHs to prevent acidification on the interior of the monopiles may thus offer benefits and risks for the ecosystem. At present, the studied WRH configuration does not appear to support many iNIS or protected epifaunal species, although outcomes are likely to vary across locations due to differences in hydrodynamics, larvae availability, and overall habitat suitability. Importantly, the long-term community development and settlement of iNIS and protected species in this newly introduced habitat requires targeted ecological monitoring of the monopile interiors, which currently is not mandatory.

Future monitoring strategies may benefit from advances in marine robotics and automated observation techniques, enabling improved and repeated surveys of monopile interiors and exteriors over longer time scales. Recent developments in smaller underwater robotic platforms, including remotely operated vehicles and autonomous underwater vehicles, provide opportunities for quantitative sampling approaches improving estimates of biomass and taxonomic resolution (Coolen et al., 2025), and the application of improved imaging systems that may enhance the quality and resolution of video-based assessments (Kingma et al., 2025). Furthermore, integrating multiple observation methods, including environmental DNA (eDNA), acoustic monitoring, and visual surveys, in an autonomous monitoring station could provide long-term complementary information and improve interpretation of ecological changes associated with water replenishment holes.

4.4. Limitations of the current study

The investigation of macrofauna was conducted using video recordings and percentage cover estimates, which limits taxonomic resolution and the detection of small or cryptic species. As a result, species-level patterns and the presence of inconspicuous taxa, including iNIS, are likely not reflected to their full extent. Nevertheless, we did find comparable numbers of taxonomic groups and phyla as other video-based studies on offshore production platforms, suggesting that broader community patterns were captured successfully (Schutter et al., 2019; Van der Stap et al., 2016). The sampling design was not fully balanced between interior and exterior recordings and monopiles, as the interior frames had a smaller AOI compared to the exterior and the number of analysed frames differed. Although the GLLVM accounted for these differences, especially rare, patchy, or small species might be affected by this. Differences in video quality might also generally affect the detectability of these species. Nevertheless, the main observed patterns are unlikely to be affected by this. Biomass estimation from video imagery proved challenging due to the limited availability of appropriate reference data and the absence of laser lines on the interior transects, forcing an estimation of area assessed. Species-specific AFDW values were derived from reference datasets that matched in terms of hard-substrate origin and the broader study region (southern North Sea and Wadden Sea). However, we did not account for aspects such as distance from shore, depth, or structure age, all of which may influence organism size and weight. Furthermore, manual counting of organisms is sensitive to error. The resulting biomass estimates should therefore be interpreted with caution. While scrape samples collected by ROVs or divers would give a more accurate representation of community composition and biomass, such sampling was not feasible under the current operational and safety constraints. Because the primary variable used for community patterns was percentage cover calculated from point classifications, the uncertainty in AOI is expected to have a limited effect on relative cover patterns. However, biomass estimates are more directly affected by uncertainty in AOI and estimation method. For this reason, the biomass estimates were not used to directly compare biomass between interior and exterior and instead were only used as proxy inputs for the water quality model to explore the potential influence of biological demand on internal environmental conditions.

In the GLLVM, depth was used as the main environmental gradient variable for both interior and exterior monopile communities. While depth provides a consistent measure across all sampling locations, water-quality inside monopiles is also likely influenced by the vertical distance to the WRHs. The observed relationship between depth and biological patterns inside monopiles may therefore partly reflect increasing vertical distance from WRHs with depth.

The water quality modelling relied on several simplifying assumptions regarding biomass, ecophysiological parameters, and ambient conditions due to data and modelling limitations. Species-specific oxygen consumption and POC rates were not available for all taxa and were therefore approximated using literature values from a limited subset of species and then applied uniformly across monopiles, depth layers, and time. As a result, the modelling is not based on a true species-specific community. Biomass normalisation and conversion to carbon biomass using non-species-specific conversion factors introduced additional uncertainties. Furthermore, ambient oxygen and particulate organic carbon concentrations were prescribed as constant boundary conditions, thereby excluding natural temporal variability and seasonal hydrographic shifts. The field measurements used for model evaluation were collected during a single monitoring campaign and therefore do not provide validation of seasonal variability in water quality conditions. Consequently, model evaluation focused on the observed order of magnitude and vertical structure of the measured concentrations rather than seasonal dynamics. Together with uncertainties in biomass estimates and ecophysiological parameters, these simplifications affect absolute concentration estimates. The model should therefore primarily be interpreted as a tool for investigating relative spatial patterns, identifying potentially limiting zones within monopiles, and assessing differences between monopile configurations, rather than for reproducing exact seasonal concentration dynamics or species-specific ecological thresholds.

5. Conclusion

This study demonstrates that offshore wind monopiles equipped with WRHs function as novel semi-enclosed artificial habitats that support epifaunal communities different from those on the exterior monopile surfaces. The combination of field observations and numerical modelling provides a unique insight into the relationship of the field-observed vertical structure of the epifaunal communities and the vertical gradients in DO and POC on the interior of the monopiles, generated by the WRHs.

Interior monopile surfaces were characterised by lower overall epifaunal cover, reduced dominance of typical offshore hard substrate taxa such as Amphipoda, Bivalvia, and Hexacorallia, and a comparatively heterogeneous community including Ophiuroidea, Serpulidae, and Porifera. In addition, accumulation of organic matter and the presence of microbial mats on interior seafloors indicate altered breakdown of organic material and potential risks for seafloor epifauna.

Due to the absence of light, restricted hydrodynamics, and gradients in POC and DO, the monopile interiors do not simply resemble common hard substrate communities. Instead, they function as an artificial cave-like environment that increases habitat heterogeneity within offshore wind farms and may contribute to local-scale biodiversity changes. However, ecological outcomes vary between monopiles and are influenced by structural configuration, highlighting the importance of design-specific effects.

Together, these findings show how engineering modifications for improved corrosion protection can also influence ecological functioning. As offshore wind energy continues to expand, this study provides a first step towards evaluating the ecological implications of WRH-equipped monopiles and similar designs that make internal spaces accessible to marine organisms. Future work should focus on design improvements for a positive contribution to biodiversity assets and long-term abiotic and biotic monitoring of species-level responses (including iNIS and protected species), habitat use by mobile species, and the microbial communities near the seabed. This will support the development of offshore renewable energy infrastructure that balances engineering optimisation with ecological outcomes.

CRediT authorship contribution statement

Leandra M. Kornau: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Birte Leutelt:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Christiaan J. van Sluis:** Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Niek Bruinsma:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Marjolijn D. Mascini:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Renate A. Olie:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation. **Frank A.G. Jacobs:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Sytske van den Akker:** Writing – review & editing, Writing – original draft, Investigation. **Eva de Haan:** Writing – review & editing, Writing – original draft, Investigation. **Eline van Onselen:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Natalia Strigin:** Writing – review & editing, Writing – original draft, Project administration. **Reindert Nijland:** Writing – review & editing, Writing – original draft. **Joop W.P. Coolen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used Microsoft Copilot and OpenAI ChatGPT to assist in language polishing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joop Coolen and Frank Jacobs report financial support was provided by The Rich North Sea. Eva de Haan, and Sytske van den Akker report indirect financial support provided by Vattenfall through a subcontract with Føn Energy Services. Natalia Strigin, Niek Bruinsma and Marjolijn Mascini report financial support was provided by Vattenfall. Joop Coolen, Niek Bruinsma, Marjolijn Mascini, Natalia Strigin, Renate Olie, Frank Jacobs, Christiaan van Sluis, and Eline van Onselen report financial support was provided by TKI Offshore Energy and RVO. Christiaan van Sluis, Renate Olie, and Eline van Onselen report that The Rich North Sea is part of the alliance Nature Regeneration North Sea. Leandra Kornau reports that financial support was provided by INSITE North Sea, TKI Deltatechnology, and Heerema Marine Contractors. All work was supported in kind by Vattenfall. The other 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. All authors declare that even though funding was received the funder did not influence the results or the interpretation thereof.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130810.

Data availability

Data are available in Supplementary Materials, and video and image files are available through the repository link in the manuscript.

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