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# Abandonment of fibreglass reinforced plastic (FRP) fishing boats in Kerala, India, and chemical emissions arising from their burning

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## Abstract

Little information exists on the fate and impacts of boats constructed of fibreglass reinforced plastic (FRP) once they reach their end-of-life. In this study, the number of abandoned fishing boats constructed of FRP or constructed of plywood-wood and sheathed by FRP has been determined along the coast of Kerala, India, and chemical emissions have been estimated when boats are burned as a means of disposal. A total of 292 abandoned boats were observed across eight coastal transects constructed around selected landing centres, with abandonment ranging from 13 to 48 per km (average = 29 $km^{-1}$). This results in the generation of 1420 kg of FRP debris (glass mat and epoxy resin) per km of coastline. A controlled combustion experiment, simulating open burning, revealed that 63% of original boat mass is emitted to the atmosphere, with the remainder forming a burnt residue. Total concentrations of polychlorinated dibenzo-*p*-dioxins and dibenzofurans emitted and remaining were found to be 2.6 ng $Nm^{-3}$ and 249.6 μg $kg^{-1}$, respectively, with respective calculated toxicity equivalence (TEQ) levels of 437.6 pg TEQ $Nm^{-3}$ in air emissions and 26.6 μg TEQ $kg^{-1}$ in the residue. These figures are equivalent to the total emission from FRP boat burning of about 17,000 μg TEQ $t^{-1}$. Burning also generates significant quantities of potentially toxic metals, with resulting concentrations of Co, Cr and Cu close to or exceeding soil guideline values. The study calls for a greater awareness of the impacts arising from boat abandonment and burning

amongst fisherman, and guidelines or regulatory protocols regarding safe and sustainable boat disposal or recycling.

**Keywords** Fibreglass reinforced plastic, polychlorinated dibenzodioxins, potentially toxic metals, toxicity equivalence, microplastics

## 1. Introduction

Fibreglass reinforced plastic (FRP) is a polyester resin-based composite, reinforced with fine strands of glass filaments in various weave patterns (Hopkinson et al., 2021). Currently, the demand for FRP is increasing, with recent estimates of annual growth rate of 7 and 4.7 percent in the Asia-Pacific region and in India, respectively (Yi, 2018). Marine applications, including boat building, account for a significant portion of the overall market share of India's FRP industry because of the durability, flexibility, ease of production, resistance and high strength-to-weight ratio of the material (bin Shamsuddin, 2003). In particular, FRP laminates have been popular on plywood and wooden boats in the small-scale fishing sector in India to protect the substrate from bio-degradation (Sreeja et al., 2006).

One of the biggest problems with boats fully or partly constructed of FRP, however, is their recycling or disposal (International Maritime Organization, 2019). Thus, while the recycling of steel ships is a significant industry (Lipi et al., 2020), there are fewer feasible recycling or disposal alternatives for small-scale fishing boats with FRP hulls (Jayaram et al., 2018). Consequently, end-of-life FRP boat abandonment is an increasing problem along the shoreline and in shallow coastal waters (Nordic Council of Ministers, 2013; Ciocan et al., 2020). Moreover, because of the composition of FRP, boats could be considered as a significant, direct source of (polyester-based) microplastics to the marine environment (Song et al., 2014).

In many countries, and in particular in developing nations, there are no standard regulatory or guidance protocols for the sustainable disposal or recycling of small, end-of-life, FRP fishing boats. Consequently, fishermen are often observed burning boats on beaches as a means of (partial) disposal and to free up space for fishing activities. While this practice has not been studied scientifically, open-burning more generally is known to result in the emission of many harmful combustion products (Lemieux et al., 2004). These include potentially toxic metals, and persistent and bioaccumulative organic compounds, like polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), that are toxic at extremely low concentrations (Fisk et al., 1998; Kelly et al., 2004).

To improve our understanding of the scale and impacts of FRP boat abandonment and burning in the coastal zone, the present study was conducted in an important fishing district (Kerala, India). Specifically, we (i) undertook a series of systematic surveys in which boat abandonment and burning was charted and tallied, and (ii) performed a controlled combustion experiment that allowed us to quantify the generation of airborne and residual PCDD/Fs and potentially toxic metals during open burning.

## 2. Materials and methods

### *2.1. Study area and site selection*

Kerala, a coastal state on the southwest coast of the Indian subcontinent with 590 km of coastline, was selected for the study. Kerala is one of India's most important marine fish producing states, with fishing and allied industries a significant source of employment and income. There are around 230,000 active fishermen and over 35,000 fishing vessels in the state that are spread across 222 coastal villages (Government of Kerala, 2015).

Eight fish landing centres and harbours were selected for study based on the number of small-scale, operational FRP fishing boats (Figure 1).

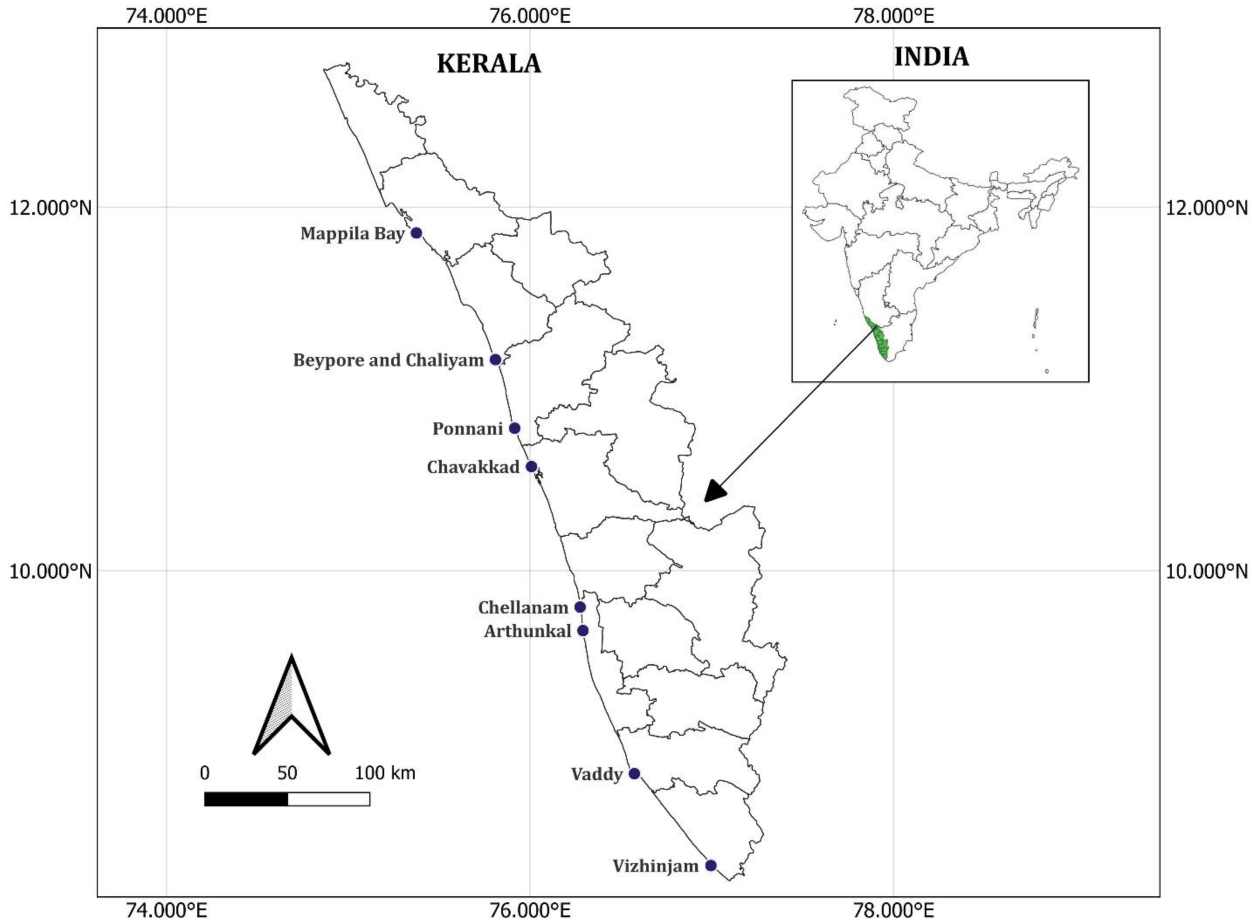


*Figure 1: Locations of the sampling sites selected for the study in the state of Kerala, India.*

### *2.2. Estimation of the extent of FRP fishing boat abandonment*

For the quantification of the extent of abandonment, discarded or end-of-life fishing boats from each site (often inverted, free of any accessories and with visible damage) were visually counted landside and waterside across a long transect (parallel to the beach) of the entire harbour or landing centre (about 0.5 to 2.8 km in total; see Figure 2 for an example). Data and information were also collected from the boat building yards near the landing centres for an assessment of the FRP materials being used for the construction of fishing boats and according to criteria outlined in Anmarkrud (2009).


*Figure 2: An example of transect performed along the curved shoreline of the harbour at Chellanam (total distance = 0.48 km).*

### 2.3. Open burning experiment

In order to evaluate the toxicity and chemical makeup and toxicity of material generated by the burning of abandoned boats, a simulated combustion study was conducted in an open burning test facility (OBTF) at the Council of Scientific and Industrial Research–National Institute for Interdisciplinary Science and Technology (CSIR-NIIST, Kerala) and described by Ajay et al. (2022). Thus, at three of the sampling sites where the practice of burning was evident, random pieces of broken boat parts from a number of FRP-sheathed abandoned vessels were collected and mixed and a representative subsample of about 10 kg was separated for analysis. The precise weight was determined using an external balance and the calibrated aluminium load cell (range 2 to 200 kg) connected to the platform of the OBTF. Material was placed in a shuffle pattern on the load cell before being ignited with a welding torch (liquified petroleum gas and oxygen), with combustion air supplied from all the four sides of the burn hut through bored ducts of a 0.2 m radius wind tunnel using an axial air blower at a constant flow rate of 30 $m^3$ $min^{-1}$. US EPA method 23 (US EPA, 1991) was followed for the sampling of air output through the burn hut stack on XAD-2 resin that had been pre-spiked with 100 pg of $^{13}C$-labelled dioxin/furan (1234 TCDF, 1234 TCDD) and 100 pg of $^{13}C$-labelled PCBs (PCB 79, PCB 60, PCB 127, PCB 159) as sampling standards. Beginning with waste ignition, real time changes in the weight of the combustion pile, along with the temperature (via a series of k-type thermocouples) at five different points in the air pathway (core of the pile, top of the pile, top of the flame, centre of the burn hut, and opening of the stack), were monitored and recorded for the duration of the experiment (about 150 min) and when smoke emission was no longer visible from the stack. Once cooled, burnt residue of about 150 g was collected through coning and quartering and after drying at 104$^{o}$C for 3 h was stored in a series of amber bottles.

### *2.4. Analysis of PCDD/Fs*

Both air and residual ash samples were spiked with 100 pg of $^{13}C$-labelled PCDD/Fs and 500 pg of dl-PCBs as internal standards before Soxhlet extraction at five siphons per hour was carried out using high purity toluene for 16 h. Extracts were removed and fractionated into PCDD/Fs + NO-PCBs and MO-PCBs + NDL-PCBs using a three-column (multilayer silica, alumina and carbon) automated system (DEXTech-Pure, LCTech, Germany). Sample fractions were concentrated to near dryness using a nitrogen evaporator (Supervap-6, FMS, USA) and spiked with syringe standards (20 pg of 1278 TCDF, 123468 HxCDF, 1234689 HpCDF, and 100 pg of PCB 70, PCB 111, PCB 170). The volume was reconstituted to 200 µL in *n*-nonane in a glass insert and analysed using GC-tqMS (Model: 7890B/7000C, Agilent Technologies, Germany).

Sample injection (4 µL) was performed in programmable temperature vaporizer mode and a DB-5MS UI 60m GC column (Agilent Technologies, Germany) was used for the effective separation of closely eluting congeners. The instrument was operated in electron ionization mode at 70 eV and multiple reaction-monitoring modes, with He as the carrier gas at a flow rate of 1 mL $min^{-1}$ and a total run time of 35.5 min. The instrument analysed each native and corresponding $^{13}C$-labelled internal standards by monitoring two different precursor ions (quantifier and qualifier) and two different product ions, respectively.

Procedural blanks were run before each sample analysis to minimise the background and cross-contamination. The on-column concentration of the lowest acceptable calibration point was taken as the specific congener limit of quantification (LOQ) and for values observed to be lower than the quantification level, the LOQ value was taken for reporting (Law et al., 2018; L'Homme et al., 2015). Internal standard recoveries not in the range of 60-120% were taken for reporting only if the congener's contribution to total toxicity equivalence (see below) was less than 10%.

### *2.5. Calculation of toxicity equivalence and emission factors*

The WHO-$TEF_{2005}$ (toxicity equivalence factors) assigned to each of the dioxin (and furan) congeners were used to calculate the total toxicity equivalence (TEQ) from their observed concentrations, *C*, as follows (van den Berg et al., 2006):

$$\text{TEQ} = \sum_{i=1}^{n}\left(C_i^{\text{PCDD}} * \text{TEF}_i^{\text{PCDD}}\right) + \sum_{i=1}^{n}\left(C_i^{\text{PCDF}} * \text{TEF}_i^{\text{PCDF}}\right) \quad (1)$$

PCDD/F air and burnt residue emission factors ($EF_{air}$ and $EF_{residue}$, respectively, and both in ng $kg^{-1}$ of burnt waste) were calculated from (Lemieux et al., 2004; Gullett et al., 2001):

$$\text{EF}_{\text{air}} = \frac{C_{\text{air}} * Q_{\text{burn hut}} * t_{\text{run}}}{m_{\text{burned}}} \quad (2)$$

$$\text{EF}_{\text{residue}} = \frac{C_{\text{residue}} * Q_{\text{residue}}}{m_{\text{burned}}} \quad (3)$$

where $C_{air}$ and $C_{residue}$ are PCDD/F concentrations in air (ng $m^{-3}$) and burnt residue (ng $g^{-1}$), respectively, $Q_{burn\ hut}$ is the flow rate of diluent air into the burn hut normalised to $0^{o}$C and 1 atm ($m^3$ $min^{-1}$), $t_{run}$ is the total run time of the experiment (min), $Q_{residue}$ is the quantity of burnt residue (g), and $m_{burned}$ is the mass of waste burned (kg).

### *2.6. Potentially toxic metal analysis*

Triplicate, 2-g samples of burnt residual ash were digested in 7 mL of concentrated nitric acid (Suprapur, Merck) in individual, capped 100 mL Teflon vessels at 150 $^{o}$C in a Nabertherm microwave for 15 min. Cooled digests were diluted to 50 mL with Milli-Q water before being analysed for As, Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn by inductively coupled plasma-optical emission spectroscopy (ICP-OES) using an Optima 2000 DV

(Perkin Elmer, Waltham MA, USA). The instrument was calibrated with blanks (dilute $HNO_3$) and a series of matrix-matched mixed standards up to 100 mg $L^{-1}$.

# 3. Results and discussion

## *3.1 General observations*

Examples of abandoned FRP fishing boats along the coast of Kerala are illustrated in Figure 3. Boats or remains thereof could be found amongst the vegetation of the back beach, lying on or partially sunken in beach sand, and moored or unmoored in shallow water, with burnt remains commonly evident along the shore.

The total number of abandoned fishing boats and the number per km at each location surveyed are given in Table 1. Overall, 11.5 km of coastline was considered and 292 boats were identified. At each location, the number of boats ranged from 17 to 72 (mean = 36.5) and the number per km ranged from 13 to 48 (mean = 29 per km).

*Table 1: Transect length and the number of abandoned boats at each location surveyed (see Figure 1).*

| Location | Transect, km | No. boats | No. boats/km |
|---|---|---|---|
| Mappila Bay | 1.4 | 42 | 30 |
| Beypore and Chaliyam | 2.8 | 37 | 13 |
| Ponnani | 1.8 | 36 | 20 |
| Chavakkad | 0.53 | 18 | 34 |
| Chellanam | 0.48 | 23 | 48 |
| Arthunkal | 1.1 | 17 | 15 |
| Vaddy | 1.8 | 47 | 26 |
| Vizhinjam | 1.6 | 72 | 45 |
| Total | 11.5 | 292 | 25 |


*Figure 3: Examples of abandoned fishing boats identified in the study. (a) A boat abandoned amongst vegetation along the backshore of a beach, (b) a boat moored in shallow water just off the shoreline, and (c) the remains of a boat partly submerged in beach sand and surrounded by significant quantities of litter.*

Abandoned fishing boats ranged from about 6 to 12 m in length, and were either constructed of FRP alone or of marine plywood or wood sheathed with FRP. Specifically, about 90% of boats appeared to be sheathed with a hull thickness of 6-8 mm and a median length of about 7 m. From discussions with fishermen and related, published research (Sukandar et al., 2019), it is estimated that sheathed boats have a working lifespan of 7 to 10 years and that FRP boats have a lifespan of more than 30 years.

The estimated material and chemical compositions of 7-m boats constructed entirely of FRP or sheathed with three layers of glass mat are shown in Table 2 based on information gathered from boat construction yards and data reported in Anmarkrud (2009). Sheathed boats are predicted to be lighter than fully FRP boats, with lower percentage contributions from the glass mat and resin and chalk powder but with significant contributions from wood, paints and copper nails.

Table 2: Estimated composition of a fully FRP 7-m boat and an FRP-sheathed 7-m boat.

| | Fully FRP | | FRP-sheathed | |
|---|---|---|---|---|
| | kg | % | kg | % |
| glass mat | 35 | 18.0 | 15 | 10.4 |
| epoxy resin | 77 | 39.6 | 27 | 18.7 |
| gel coat | 7 | 3.6 | 0 | 0 |
| pigment | 0.7 | 0.4 | 0 | 0 |
| accelerator | 2.2 | 1.1 | 0.73 | 0.5 |
| catalyst | 0.17 | 0.1 | 0.05 | 0 |
| acetone | 2.35 | 1.2 | 1.57 | 1.1 |
| chalk powder | 70 | 36.0 | 20 | 13.8 |
| wax | 0.2 | 0.1 | 0.2 | 0.1 |
| wood | 0 | 0 | 60 | 41.5 |
| copper nails | 0 | 0 | 7 | 4.8 |
| paint | 0 | 0 | 13 | 9.0 |
| total | 194.6 | | 144.6 | |

Based on the dimensions of a representative 7 m boat, coupled with the relative abundances and compositions of sheathed and fully FRP boats (about 9:1) and their respective compositions (Table 2), we estimate an average mass of glass mat plus resin of about 49 kg per boat. This is, therefore, equivalent to between about 640 and 2350 kg (mean = 1420 kg) of FRP debris per km of affected coastline.

Examples of discarded, sheathed fishing boats that had been burned as a means of disposal are shown in Figure 4. There is limited information on the occurrence and impacts of this practice but the International Maritime Organization (2019) acknowledges the likely emission of potentially hazardous chemicals into the atmosphere.

*Figure 4: The residues of discarded, sheathed fishing boats that had been burned along the back beach.*

### ***3.2. PCDD/F release from boat burning***

The highest temperature observed during the combustion experiment (421°C) was at the core of the pile, and the pile temperature was in the range of 200-400 °C for 58% of the total duration. Chloride abundance is critical for the formation of PCDD/Fs, with most of the open burning activities of boat hulls taking place along beaches where the inorganic chlorine content is typically very high. However, and more generally, organic chlorides play a greater role in the formation of PCDD/Fs at 300 to 400°C (Zhou et al., 2019), and these are supplied in the form of a plethora of compounds as adhesives, fillers and additives in the boat construction materials shown in Table 2 (Abbood et al., 2021).

The OBTF experiment resulted in the loss of 63% of the initial 10-kg mass during, with the remaining 37% left in the burn hut platform. The analytical recoveries of the internal standards ranged from 45.2 to 107.9%, and congeners with recoveries lower than 60% were considered in the final calculations only if their contribution to the total concentration was < 10%. Within these criteria, the concentrations of PCDD/Fs emitted into the atmosphere and in the burned residue were found to be 2.6 ng $Nm^{-3}$ and 249.6 μg $kg^{-1}$, respectively, and the respective calculated toxicity equivalence levels were 437.6 pg TEQ $Nm^{-3}$ in air emissions and 26.6 μg TEQ $kg^{-1}$ in the burnt residue. These figures yield values for $EF_{air}$ and $EF_{residue}$ of 138 μg TEQ $t^{-1}$ and 16,900 μg TEQ $t^{-1}$, with a total emission from abandoned boat open burning of about 17,000 μg TEQ $t^{-1}$. Although there are no other comparable values reported in the scientific literature for fibreglass burning, UNEP (2013) provide guideline TEQ values for various practices of controlled and uncontrolled combustion that are based on published information and these are shown in Table 3. Thus, open burning of FRP-sheathed boats generates air emissions (as TEQ $t^{-1}$) that are comparable with the open burning of circuit boards, vehicle fires, and the incineration of wood and biomass with no air pollution control systems (APCS), greater than the open burning of wood and domestic wastes and municipal and wood-biomass incineration with good APCS, and less than house and waste dump fires, low technology municipal incineration and the open burning of electrical (and presumably polyvinyl chloride-based) cables. Residue estimates shown in Table 2 are based on different approaches (e.g. fly ash, bottom ash, land contamination) but it is clear that the open burning of FRP-sheathed boats results in extremely high total emissions that exceed all other practices reported.

Table 3: A comparison of TEQ air emissions and residual concentrations derived from FRP-sheathed boat burning and guideline values for a range of other controlled and uncontrolled combustion practices (UNEP, 2013).

| | air, μg TEQ $t^{-1}$ | residue, μg TEQ $t^{-1}$ |
|---|---|---|
| waste wood-biomass incineration, full APCS | 1 | 0.2 |
| municipal waste incineration, good APCS | 30 | 7 |
| open burning of domestic waste | 40 | 1 |
| open burning of wood waste | 60 | 10 |
| waste wood-biomass incineration, no APCS | 100 | 1000 |
| vehicle fires | 100 | 18 |
| open burning of circuit boards | 100 | |
| **open burning of FRP-sheathed boats (this study)** | **138** | **16,900** |
| fires at waste dumps | 300 | 10 |
| house fires | 400 | 400 |
| municipal waste incineration, low technology | 3500 | 75 |
| open burning of cables | 12,000 | |

### *3.3. PCDD/F congener profiles from boat burning*

The concentrations and percentage equivalencies of individual PCDD/F congeners in air and burned residue arising from boat burning are shown in Figure 5. The ratios of PCDDs to PCDFs emitted into the atmosphere were 0.33:0.67 and 0.44:0.56 based on concentration and toxicity equivalence, respectively. By contrast, the residual ash sample contained PCDDs to PCDFs at ratios of 0.97:0.03 and 0.96:0.04, respectively. It was found that lower chlorinated furan species (and in particular, 2378-TCDF and 23478-PeCDF) were the predominant congeners in the air sample but higher chlorinated dioxins (mainly 123478-HxCDD, 123678-HxCDD, 1234678-HpCDD and OCDD) were predominant in the residue.

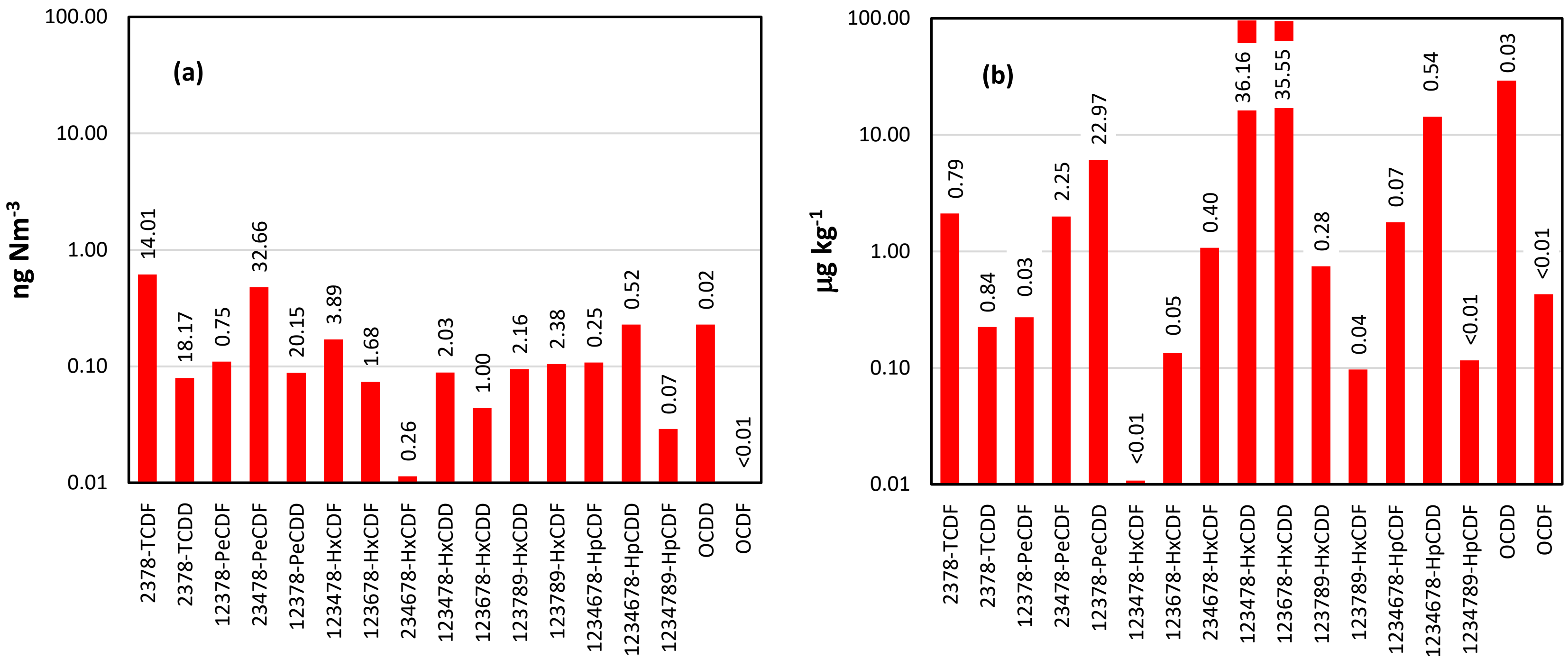


Figure 5: Contributions, by mass, of different congeners to (a) air emissions and (b) burnt residue samples and, annotated, percentage contributions to total TEQ.

There are three possible mechanistic pathways of dioxin formation during the combustion of FRP boat residues: homogenous precursor condensation, heterogeneous precursor condensation, and de-novo synthesis. De-novo synthesis and homogenous condensation mechanisms lead to higher PCDFs than PCDDs whereas heterogeneous condensation generates more PCDDs than PCDFs, while de-novo synthesis and heterogeneous condensation lead to the higher concentrations of higher chlorinated congeners whereas homogenous condensation favours lower chlorinated species (Everaert and Baeyens, 2002). Because air emission is dominated by lower chlorinated furan congeners and the burnt residue is dominated by higher chlorinated dioxin congeners, we presume that the homogenous precursor mechanism was prevalent during the combustion stage but significant heterogeneous precursor condensation also took place in the soot phase.

### *3.4. Potentially toxic metals in burnt residue*

The concentrations of potentially toxic metals (and the metalloid, arsenic) in the burnt ash residue are shown in Table 4. For comparison, a general indication of the maximum allowable concentrations for metals in soils and as reported by Chiroma et al. (2014) are also shown. In most cases, concentrations in the ash are lower than guideline soil values and presumably reflect the general contamination of many of the most important source materials that are used to construct sheathed boats (Table 2), like wood, chalk, resin and glass mat. By contrast, concentrations of cobalt, chromium and copper and close to or exceed soil guideline values, suggesting that these metals are of greater concern from an environmental perspective and from a health perspective for fishermen engaged in the burning process. It is likely that these metals are derived from functional additives that are employed in specific components of the boats, and in particular accelerators, catalysts and hull paints (Table 2). Specifically, chromium, in the form of chromate, is used in primer applications (Lin et al., 2019), copper, as copper(I) oxide or copper(I) thiocyanate, is commonly encountered in antifouling coatings (Turner, 2010), and cobalt, as cobalt naphthenate, cobalt octoate, or cobalt neodecanoate, is often used as a curing accelerator (Matuskova et al., 2021).

Table 4: Concentrations of potentially toxic metals (as mean and one standard deviation; *n* = 3) in the burnt ash arising from abandoned FRP-sheathed boat burning, and maximum allowable concentrations in soil reported by Chiroma et al. (2014).

| metal | burnt ash, mg kg$^{-1}$ | max. allowable in soil, mg kg$^{-1}$ |
|---|---|---|
| Cr | 256.5 ± 22.7 | 100 |
| Co | 46.08 ± 4.56 | 50 |
| Zn | 17.30 ± 4.10 | 300 |
| Cu | 275.3 ± 39.7 | 100 |
| Pb | 6.33 ± 1.14 | 100 |
| Mn | 61.04 ± 13.64 | 2000 |
| Cd | 0.58 ± 0.15 | 3 |
| Ni | 2.66 ± 0.51 | 50 |
| As | 0.58 ± 0.18 | 20 |

### *3.5. Conclusion*

The abandonment and disposal by burning of FRP-sheathed fishing boats is one of the practices along the Kerala coast of India and yet is unregulated. Impacts relating to aesthetics and loss of public access, and that are more generally associated with boat abandonment (Turner and Rees, 2016), are clearly evident. However, less obvious impacts arise through the contamination of the marine environment by microplastics, fibrous minerals and paint particles (Hopkinson et al., 2021) and, through open burning, the generation of various metals and highly toxic PCDD/Fs that are both airborne and components of the residual ash. TEQ values for chlorinated organic compounds arising from boat burning exceed values for many other combustion activities of municipal and harmful wastes with or without APCS. Options to eliminate or minimise boat abandonment and burning include introducing regulations that are enforceable, making boat owners aware of the hazards of both practices, and the introduction of sustainable schemes to incentivise the safe disposal or recycling of materials (Nordic Council of Ministers, 2013; Byrnes and Dunn, 2020; Martinez-Vazquez et al., 2022).

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**Authors' contribution Statement**

N. Manju Lekshmi: Conceptualization, Methodology, Initial drafting
Sreejith S. Kumar: Data curation, laboratory analysis, drafting
P. Muhamed Ashraf : Analysis
K. A. Martin Xavier : Editing
K. P. Prathish :Laboratory analysis, Supervision
S.V. Ajay : Laboratory analysis
Leela Edwin : Supervision
Andrew Turner : Reviewing, Editing and validation

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## Data availability statement

Data that support the findings of this study are available from the corresponding author upon request.

## Declarations

### Ethical responsibilities of authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of authors" as found in the Instructions for Authors.

**Conflict of interest:** The authors declare no competing interests.

### Consent for publication

We confirm that all authors have read the manuscript and agree to its submission in Environmental Monitoring and Assessment.

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