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An Insight into Environmental Impacts within Plastic Waste Recycling Factories

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Plastic recycling plays a vital role in maintaining a circular economy as it helps conserve natural resources and minimizes the environmental impact of plastic waste. This activity, however, can cause adverse effects on the surrounding environment due to untreated wastewater and emissions. This study conducted a thorough investigation in terms of water, wastewater, and air quality at the most prominent plastic recycling facility in a craft village in the northern province of Vietnam. The initial results revealed that the groundwater quality was not affected by the recycling activities. The untreated wastewater contained high concentrations of chemical oxygen demand (COD), biological oxygen demand (BOD_5), and suspended solids (SS), i.e., 1010 mg/L, 269 mg/L and 262 mg/L, respectively. The coliform was ten times higher than the standard. For the air quality, PM_{10}, $PM_{2.5}$, noise, and VOCs were of the most concern, with concentrations of 256 μg/m^3, 214 μg/m^3, 86.6 db and 730 μg/m^3, respectively, within the factories. These values were all higher than both Vietnam and international standards. This was the reason for causing unpleasant smells and noise, as well as the frequent sewage blockage that the villagers are facing daily. Heavy metal concentrations were mostly found within acceptable values for both wastewater and air samples. Risk assessment revealed the pollutants of concerns in the order of $PM_{2.5}$ > VOCs > PM_{10}, SO_2, Ni > Cd > Pb > NO_2, As. Proper mitigations were proposed for better working and living environments in the plastic recycling villages.

Keywords: working environment, plastic waste, recycling factories, air and water pollution, mitigation solutions.

Introduction

Asia has become one of the most significant regions for plastic production and consumption. The amount of plastic waste generated by Asian countries was estimated about 121 million tons (Mt) in 2015. The total Asian production quantity of major plastic resins was 82 Mt, of which China's share was 44.79 Mt, followed by

India and Korea, with 14.17 and 13.68 Mt/year, respectively (Yangyang et al., 2021). High production leads to a greater concern in plastic waste treatment and recycling. In Japan, more than 9 Mt of plastic waste was generated in 2017, only 23% of which was recycled (Jang et al., 2020). Plastic waste generation in South Korea increased from 6 Mt in 2009 to about 8 Mt in 2017, however, only about 44.5% was recycled as materials or energy. In 2019, the value of recycled plastic waste in China was 137 million US dollars (Straková et al., 2022).

The total domestic consumption of plastics in Vietnam was estimated at about 3.57 Mt, and 20% of which was sent to landfill, burning, or disposal into the environment. Thus, 80% was recycled (WWF, 2023). The development of plastic recycling villages has been currently not well controlled and revealed many disadvantages such as (i) small recycling scale (mostly households scale), (ii) outdated recycling technology that does not fully recover valuable components in solid waste, and (iii) poor working environment. In general, most plastic recycling technologies are at a low-medium level and are mainly applied to small and medium-sized enterprises and units.

Poor plastic recycling processes have created environmental and health issues for the surrounding residents. Water pollution was observed by Sajjad et al. (2022) in which microplastics were claimed to play an important role in the transportation of toxic chemicals such as plasticizers, polycyclic aromatic hydrocarbons (PAHs), antibiotics, and potentially toxic elements (PTEs) into the water bodies. Incineration of plastic waste releases toxic gases like dioxins, furans, mercury and polychlorinated biphenyls into the atmosphere, which can cause health effects, especially for old people, children, and people with lung and cardiovascular diseases. Burning of Polyvinylchloride liberates hazardous halogens and polluted gases, the precursors of climate change phenomenon (Verma et al., 2016). Besides, direct inhalation of microplastics-polluted air also affects the respiratory system, in particular causing inflammatory symptoms. Some types of fibrous microplastics can remain in the lungs for up to 180 days (WWF, 2023). The high concentration of total VOCs in the vicinity of the plastic recycling factory caused mucocutaneous and respiratory symptoms among the residents in the closest area to the factory (Takashi et al., 2012). Some symptoms were significantly increased among the residents within 500 m of the factory compared with residents of an area 2800 m from the factory. A study conducted by Zhao also showed the same results, the odds of residents living 500 or 900 m away from the facility reporting mucocutaneous and respiratory symptoms using a reference group of residents 2800 m away (Zhao et al., 2017).

It seems most of the research in Vietnam and worldwide evaluated the environmental pollution and health problems caused by plastic recycling factories in general (Ni et al., 2016; Zhao et al., 2017; Salhofer et al., 2021), however, the working environment within plastic recycling factories has not been studied in detail. Therefore, this study conducted a thorough investigation of air and water quality within the largest plastic waste recycling factory in a craft village in Vietnam. A more sustainable approach to improve the working conditions shall be introduced for plastic waste recycling factories.

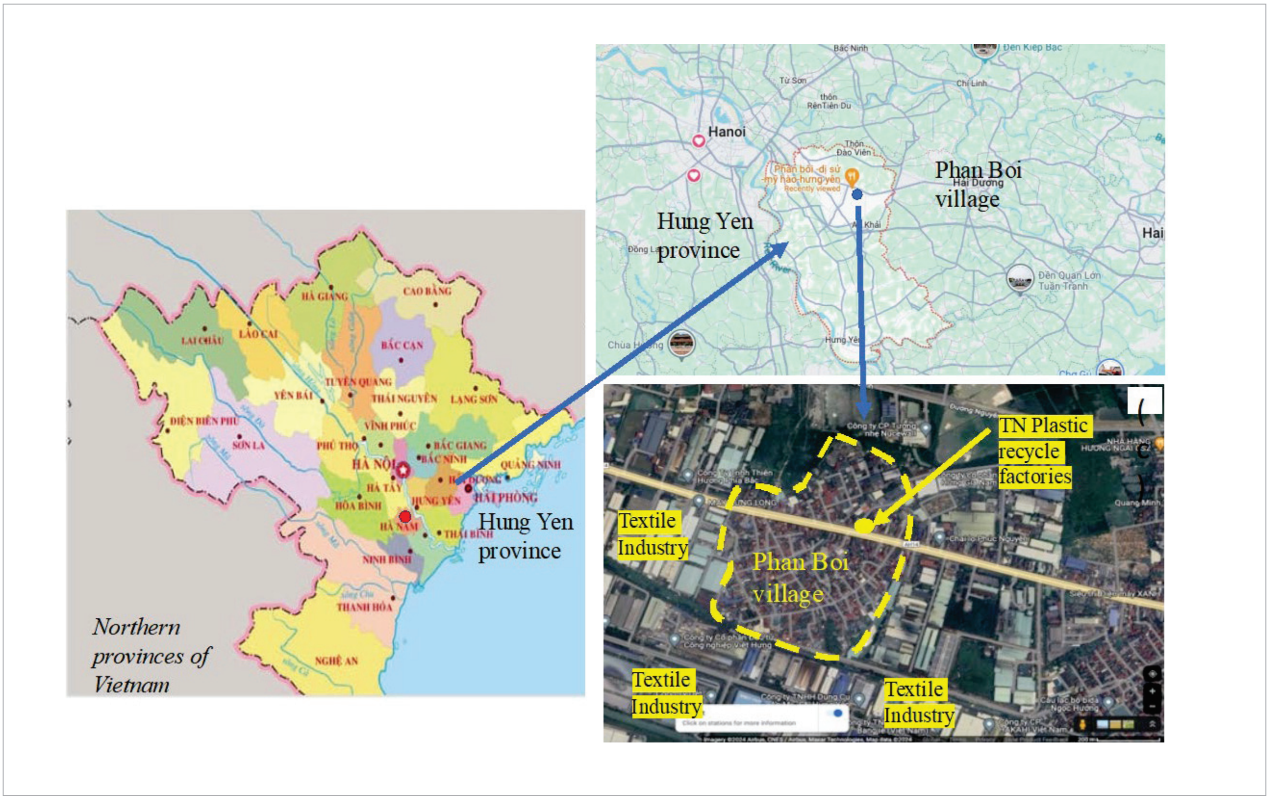
Materials and Methods

Site description and sample selection

Phan Boi plastic recycling craft village is located on Highway 5, My Hao town, Hung Yen province. About 200 households are living in this village, majority of them are involved in the recycling industry (130 households or 65%). Each household/facility has spaces for plastic recycling and living activities. Thus, not only the working environment but also the living environment would be of concern. The village had a total processing capacity of between 100-200 tons of input waste material daily, sourced primarily from the domestic plastic waste market. The material always enters the village mixed, so a sorting process is necessary (Salhofer et al., 2021). The village is located in a densely populated residential area with no separation for industrial activities (*Fig. 1*).

The Tuan Nhu (TN) plastic recycling facility is the largest one with eight recycling factories (*Fig. 2*) in approximately one hectare area and it has about forty to fifty workers. The plastic recycling capacity is 2000–3000 tons per month or 67–100 tons per day. The main products are black and white high-density polyethylene (HDPE) and polypropylene (PP) plastic pellets. The recycling facility also produces clean plastic pieces of

Fig. 1. *Studied area*



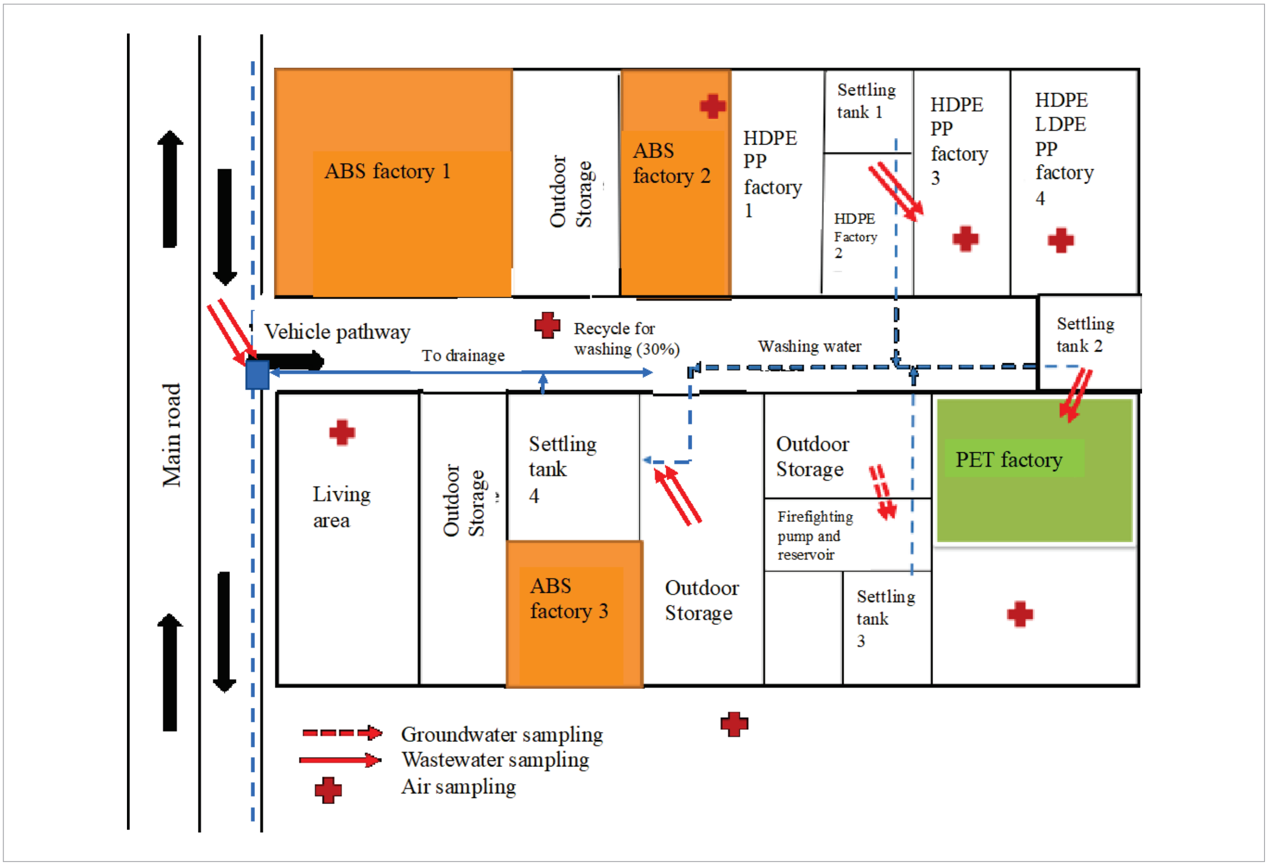
polyethylene terephthalate (PET), low density polyethylene (LDPE), and acrylonitrile butadiene styrene (ABS) plastics. For the PET and ABS factories, the waste plastics are shredded, sorted and washed with water. For the HDPE and LDPE, the waste plastics are sorted, shredded, washed, melt to make the pellets. Thus, these factories could generate dust, bad smell/emissions and polluted wastewater that might affect the surround areas.

For a better understanding of the potential impacts on water and air quality within the facility, the samples were selected as below:

- Groundwater samples from the water reservoir, which is adjacent to the well. This source of water is used for domestic use and plastics washing.
- Wastewater samples from four locations: the settling tanks of HDPE factory and PET factory, the washing-water storage tank and the drainage manhole in front of TN facility. It should be noted that in the HDPE/PET factories, the settling tanks were used to store the washing water after the cleaning process for each type of plastic. The settling tank in the HDPE factory also stored the cooling water from the pellet making process. To save the water, 30% of the washing water, after being settled, was reused for washing process in the factory. That's the reason why it was analysed to see if the quality was good for reuse.
- The air samples were targeted from the emissions from the plastic heating process, ambient air quality in and around the recycling site. Thus, the air sampling locations were selected based upon the following: (i) Areas with plastic melting/extrusion processes (in door); (ii) Sites where there was a risk of long-term exposure (living area) and (iii) Areas outside the factory site at varying distances (factory yard 0 m, 100 m and 200 m, following the main wind direction)

Locations for water and air samples are shown in the *Fig. 2*. It should be noted that the two locations for the air samples outside the facility were not included in the sampling layout. In addition, the TN facility's owner is living with his family in the "living area". It is a very typical model of this village that factories and houses are in the same place.

Fig. 2. *Layout of groundwater, wastewater and air sampling locations within TN plastic facility*



Sample analysis

Ground water, wastewater and air samples were taken and preserved according to the Vietnam national standard for sampling (TCVN 6663-3:2016 or equivalent ISO 5667-3:2012) and then transferred to a certified lab at Vietnam National University for analysis, following the standards (Rice et al., 2012).

Risk assessment

Based on the analyzed data, a brief description of the risk was discussed in this paper using the Fine-Kinney method (Havula et al., 2014). The following risk calculation equation were used:

$$Consequence \times Exposure \times Probability = Risk\ Score \quad (1)$$

In which:

- Consequence is most probable result of the accident (e.g. Minor cuts: 1 point, Non- permanent disability: 5 points, Permanent disability: 15 points, Very serious, fatality: 25 points, multiple fatalities: 50 points, numerous fatalities: 100 points)
- Exposure is the frequency of the exposure to the hazard (e.g. Every 5 years: 0.5 point; every 2–4 years: 1 point, Every year: 2 points, Every week: 3 points, Every day: 6 points, Many times daily: 10 points)
- Probability is likelihood that the consequence will occur and the individual is exposed to the hazard (e.g. Never happened: 0.5point, Possible coincidence: 1 point, Unusual sequence: 3 points, Quite possible: 6 points, Almost certain: 10 points).

The risk score shall be classified from low risk (10–49 points), to medium risk (50–99 points), substantial risk (100–299 points), high risk (300–499 points) and extreme risk (>500 points). In the extreme risk, the activity must not be implemented, and an alternative must be found. While for the medium to high risk, management approval is required. For the low risk, only caution must be made.

Results and Discussions

Assessment of groundwater quality

With the concern of contaminating the groundwater, which is used for domestic supply, the samples from the groundwater reservoir were collected and analyzed. They are groundwater pumped from the adjacent well. The results are presented in *Table 1*.

According to *Table 1*, the groundwater was not contaminated with heavy metals. It has only some concerns with Fe ion and coliform concentrations. They are common impurities in groundwater in general (Naily et al., 2023). This meant the plastic recycling activities did not affect the groundwater quality in the surroundings. This water source can be safely utilized as a water supply for domestic use after iron removal and disinfection.

Table 1. *Groundwater quality inside the TN plastic recycling facility*

No	Water parameter	Results	QCVN 09-MT:2023/BTNMT
1	Total hardness (as mg/L $CaCO_3$)	47±5.0	500
2	As (mg/L)	<0.0015	0.05
3	Cd (mg/L)	<0.0002	0.005
4	Pb (mg/L)	<0.006	0.01
5	Total Cr (mg/L)	<0.006	-
6	Cu (mg/L)	<0.003	1
7	Zn (mg/L)	<0.031	3
8	Ni (mg/L)	<0.002	0.02
9	Mn (mg/L)	0.43±0.01	0.5
10	Hg (mg/L)	<0.0003	0.001
11	Fe (mg/L)	**8.0±0.2**	5
12	Coliform CFU/100 mL	**11±1.0**	3

Note: QCVN 09-MT:2023/ BTNMT: National technical regulation for groundwater quality

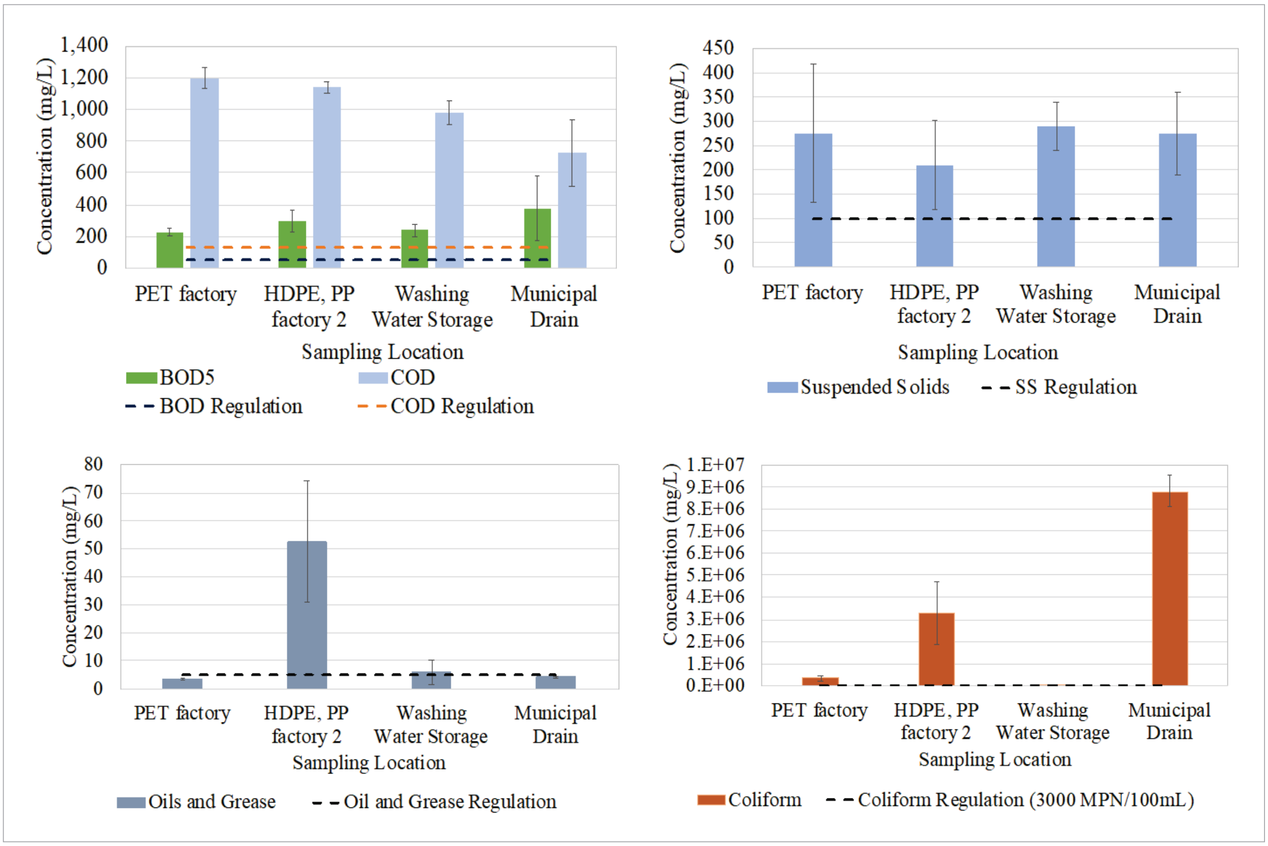
Assessment of wastewater quality

The analytical results showed that the heavy metal and the nutrient concentrations in the wastewater samples were all within the acceptable Vietnam national regulations for industrial wastewater discharge (QCVN 40:2021/BTNMT, column C). However, the following contaminants including COD, BOD5, SS, iron, oil and grease, and coliform were above national standards (*Fig. 3*).

As seen in *Fig. 3*, both COD and BOD_5 concentrations at all factory locations were above the national discharge limits for industrial wastewater in Vietnam. The recommended COD concentration limit is 130 mg/L, whereas the average concentration of COD across the site samples was approximately 1010 mg/L, almost nine times higher than the allowable level. Similarly, BOD_5 concentrations were high throughout the treatment process, with an average concentration of 286.6 mg/L, more than five times higher than the recommended concentration of 50 mg/L. The lowest COD and BOD_5 concentrations were recorded in the municipal drain outside the facility. This finding is difficult to interpret, as the drain likely contains a mixture of effluent from both the recycling factory and the nearby households. The very high COD concentration was probably due to the leaching of plastic additives, including plasticizers (Kubwabo et al., 2009), volatile organic compounds (Floyd et al., 2017; Davis et al., 2019), flame retardants or curing agents (Cheng et al., 2020) during the extrusion and granulation process or washing the plastic waste. It is the reason why the COD concentrations were highest at the HDPE and PET factories, followed by one in the washing water.

It was reported by the facility's owner that approximately 1 m^3 of wastewater was generated per tonne of plastic products. Considering the facility's production capacity is 2000–3000 tons, it generates approximately 2000–3000 m^3/month of wastewater. Of this value, 30% is recycled, while the remaining 47 to 70 m^3/d is discharged into local water bodies untreated due to the absence of an onsite wastewater system. The high loading of organics from this amount of wastewater discharged daily without treatment could have tremendously adverse impacts on the receiving rivers and lakes. Specifically, it depletes dissolved oxygen levels inside these bodies. The untreated and high COD, BOD_5 from the recycling facilities was probably the reasons causing the high levels of BOD_5 in water bodies surrounding Phan Boi Village, My Hao town based on the 5-year environmental report (HY DONRE, 2021). They were all beyond the allowable limits specified by the QCVN 08-MT:2023/BTNMT. In fact, the levels of BOD5 and COD in these water bodies are closely linked to the outputs and effluents from not only plastic recycling

Fig. 3. *Water and wastewater quality at the studied sites*



factories, but also their surrounding facilities. *Fig. 1* illustrates the textile companies and residential areas besides clusters of plastic recycling factories. The domestic wastewater from residential areas was not collected and treated as well. The continuous discharge of these high levels of polluting effluents most likely leads to the deterioration of the water quality and changes the physicochemical characteristics of the receiving water bodies.

The recommended limit for suspended solids (SS) is 100 mg/L, whereas the factory effluent had an average of 262.4 mg/L, more than double the acceptable values (*Fig. 3*). Due to the nature of recycling processes in the factory, it is likely that a considerable portion of the suspended solids consists of microplastics from small plastic factories that discharge into the wastewater. The high suspended solids might be contributed by the microplastics generated during the sorting, shredding and washing the plastic wastes. Although a simple settling tank was installed in each factory, removing all the SS including microplastics was insufficient. Additionally, the piled-up waste plastics along the internal way were exposed to weathering conditions such as sunlight (ultraviolet radiation), O_2 and precipitation that could increase the brittleness of plastics into the runoff water into the drainage (Salhofer et al., 2021), which increases the SS concentration in the wastewater stream. The accumulation of these SS, eventually, caused clogging in the drainage pipes, either right outside each household or become the worse in the downstream. According to Gerdes et al. (2019) it was imperative that microplastics were taken into consideration due to their potentially serious impacts on aquatic ecosystems and human health. The results helped answer one of the initial questions about the washing water's quality. With high SS and COD, the washing water, after being settled, were found not to be qualified for reuse. The factories should only utilize the groundwater for cleaning plastic wastes. Otherwise, a good compacted wastewater treatment system should be used to remove BOD_5, and SS (Altieri et al., 2021).

The oil and grease were an issue only at the HDPE, PP factory since it was 10 times higher than the standard. It could be due to the leaching of plastic additives, including plasticizers and curing agents, or cleaning agents used during the washing process. Oil and grease have low biodegradability in the natural environment, which can result in adverse environmental impacts, such as fish asphyxiation, fouled shorelines and beaches, drowning fauna such as birds or ducks, and clogging pipelines (Eljaiek-Urzola et al., 2019). In addition, grease impedes the transport of garbage and floating substances in the drainage system, narrowing the sewer (Williams et al., 2012) and potentially causing flooding during the rainy season, especially when combined sewers have been used commonly in developing countries like Vietnam.

The average coliforms were measured at $3.12 \cdot 10^6$ CFU/100mL, which was significantly higher than the limit (3000 CFU/100mL). The highest coliform concentration was recorded in the municipal drain, with an average of $8.8 \cdot 10^6$ CFU/100mL, which was possibly influenced by the discharge of domestic wastewater from the household. High levels of coliform concentration in PET factory ($3.3 \cdot 10^5$ CFU/100mL) and especially HDPE, PP factory ($3.3 \cdot 10^6$ CFU/100mL) were probably due to the dirt from the plastic wastes. Thus, personal protection devices should always be applied to workers who manually sort the plastic waste daily.

Assessment of air quality

The indoor and outdoor air quality results are presented in *Table 2* and *Table 3*, which also include the standard

Table 2. *Indoor air quality results*

Parameter	Unit	Inside the House	ABS	HDPE	HDPE PP	PET	Vietnam Standard[a]	Australian Standard	European Union Standard	WHO standards	US EPA
			Factory 1	Factory 2	Factory 3	Factory					
Noise	db	53.7	**72.4**	**86.6**	**82.9**	**81.1**	85[b]	85	85	75	70
PM_{10}	µg/m^3	31	16	**256**	23	15	100	50	50	50	150
$PM_{2.5}$	µg/m^3	**28**	15	**214**	18	13	50	25	20	25	35
CO	mg/m^3	<1.16	1.16	1.16	1.16	1.16	10	9 ppm (10.31 mg/m^3)	10	10	9 ppm (10.31 mg/m^3)
NO_2	mg/m^3	<0.19	<0.19	<0.19	<0.19	<0.19	0.1	0.08 ppm (0.151 mg/m^3)	0.2	0.2	100 ppb (0.188 mg/m^3)
O_3	mg/m^3	<0.01	<0.01	<0.01	<0.01	<0.01	0.1	0.065 ppm (0.128 mg/m^3)	0.12	0.1	0.070 ppm (0.137 mg/m^3)
SO_2	mg/m^3	<0.27	<0.27	<0.27	<0.27	<0.27	0.1	0.02 ppm (0.052 mg/m^3)	0.125	0.02	75 ppb (0.197 mg/m^3)
NH_3	mg/m^3	0.027	0.008	0.008	<0.007	0.056	-	17	-	-	-
Hg	mg/m^3	<0.00003	<0.00003	<0.00003	<0.00003	<0.00003	-	0.01	-	0.001	-
Cd	mg/m^3	<0.0019	<0.0019	<0.0019	<0.0019	<0.0019	-	0.01	5 ng/m^3 (0.000005 mg/m^3)	5 ng/m^3 (0.000005 mg/m^3)	-
As	mg/m^3	<0.0019	<0.0019	<0.0019	<0.0019	<0.0019	-	0.05	6 ng/m^3 (0.000006 mg/m^3)	6.6 ng/m^3 (0.0000066mg/m^3)	-
Total Cr	mg/m^3	<0.001	<0.001	<0.001	<0.001	<0.001	-	0.5	-	0.001	-
ZnO dust	mg/m^3	<0.044	<0.044	<0.044	<0.044	<0.044	-	10	-	-	-
Ni	mg/m^3	<0.0052	<0.0052	<0.0052	<0.0052	<0.0052	-	0.12	20 ng/m^3 (0.00002 mg/m^3)	25 ng/m3 (0.000025 mg/m^3)	-
Cu	mg/m^3	<0.0052	<0.0052	<0.0052	<0.0052	<0.0052	-	0.2	-	-	-
Pb	mg/m^3	<0.0019	<0.0019	<0.0019	<0.0019	<0.0019	0.0000015	0.0005	0.0005	0.0005	0.00015

Note: *[a]TCVN 13521:2022 standard on indoor air quality; [b]QCVN24:2016/BYT national regulation on noise at workplaces, Australian Standard (EPA Victoria, 2018), European Union Standard (EC, 2021), WHO standards (WHO, 2000, WHO, 2021a; WHO, 2021b), US EPA (US EPA, 2021)*

Table 3. *Outdoor air quality results*

Parameter	Unit	Factory's yard	Residential yard (100m West)	Residential yard (200m West)	Vietnam Standard	Australian Standard	European Union Standard	WHO standards	US EPA
PM_{10}	µg/m³	**55.2**	42.3	-	150	50	50	50	150
$PM_{2.5}$	µg/m³	**52.8**	**37.3**	-	50	25	20	25	35
CO	µg/m³	<2600	<2600	-	30.000	9 ppm (10310 µg/m³)	10000	10000	9 ppm (10.310 µg/m³)
NO_2	µg/m³	23	20	-	200	0.08 ppm (151 µg/m³)	200	200	100 ppb (188 µg/m³)
SO_2	µg/m³	62	57	-	350	0.02 ppm (52 µg/m³)	125	20	75 ppb (197 µg/m³)
O_3	µg/m³	<10.0	<10.0	-	200	0.065 ppm (128 µg/m³)	120	100	0.07 ppm (137 µg/m³)
NH_3	µg/m³	<7.0	<7.0	-	200	17000	-	-	-
Cd	µg/m³	<0.008	<0.008	-	0.4	10	5 ng/m³ (0.005 µg/m³)	5 ng/m³ (0.005 µg/m³)	-
Ni	µg/m³	<0.13	<0.13	-	1	120	20 ng/m³ (0.02 µg/m³)	25 ng/m³ (0.025 µg/m³)	-
Pb	µg/m³	<0.08	<0.08	-	1.5	0.5	0.5	0.5	0.15
VOCs	mg/m³	**0.73**	**0.56**	0.2	-	-	-	-	0.5

Note: *"-": Not applicable. aTCVN 13521:2022 standard on indoor air quality; bQCVN24:2016/BYT national regulation on noise at workplaces, Australian Standard (EPA Victoria, 2018), European Union Standard (EC, 2021), WHO standards (WHO, 2000, WHO, 2021a; WHO, 2021b), US EPA (US EPA, 2021)*

values from Vietnam (TCVN 13521:2022; QCVN24:2016/BYT), Australian standard (EPA Victoria, 2018) and the European Union standard (EC, 2021), United State Environmental Protection Agency (US EPA, 2021), and World Health Organization (WHO 2000, 2021a, 2021b) for assessment and comparison. It can be observed that certain parameters are not of significant concern. These include Hg, Cd, As, Cr, ZnO, Ni, Cu and Pb concentrations, which were all below the Vietnamese standards. Nevertheless, due to the limit of measurement devices, it was impossible to compare these values to worldwide standards. The most noticeable and comparable data was for noise, PM_{10}, $PM_{2.5}$ and VOCs.

Compared to all set limits, the noise recorded within the onsite housing (53.7dB) was well within the standards. It could be due to the fact that the house was far from the nosiest factories (HDPE factories) and had good sound isolation walls. For other indoor processing areas, the noise levels were 72.4dB, 86.6dB, 82.9dB, and 81.1dB for ABS Factory 1, HDPE and PP Factory 2, HDPE and PP Factory 3, and PET Factory, respectively. Most of these values complied with the standards of Vietnam, Australia and the European Union (85db), except for HDPE Factory 2, which exceeded both US EPA and WHO standards. The noise levels inside the TN plastic recycling facility were comparable to those in the wood processing factory, in which the average noise level was below the allowable standard, and some areas exceeded the permissible threshold by 1–2% (Corlan et al., 2022). The main reason is outdated machinery and equipment, not regularly maintained according to the manufacturer's promotions, causing noise (HY DONRE, 2021). From this, it can be concluded that the noise across all indoor areas of the factories (except for indoor housing) needs some attention, either conducting better machine maintenance or applying better personal protection equipment to protect workers' health and safety.

Additionally, the PM10 levels recorded within the onsite housing were well within the limits. Only in the HDPE and PP Factory 2, the PM10 concentration was 256 µg/m³, exceeding limits in all the standards. One should be noted that in the HDPE and PP factory 2 occurs all the activities such as washing, melting and granular extrusion. The melting and extrusion process was the main cause of significant emissions (EPA Victoria, 2018).

Hoffer et al. (2020) revealed that the emission factor of PM10 from burning PP waste was 33±18 mg/g, much higher than burning wood (2.1±0.7 mg/g). High PM10 in the atmosphere might cause wheezing, chest tightness, or difficulty breathing as PM10 particles were small enough to get into the throat and lungs (EPA Victoria, 2018). It was evident that even small PM increases were costly for society and could lose millions of dollars per year due to human health damage (Vega et al., 2021).

Regarding $PM_{2.5}$, which is more dangerous than PM_{10} as it can be easier to get into the throat and lung, it also showed concerns for the case of HDPE and PP Factory 2. The $PM_{2.5}$ value at HDPE and PP Factory 2 of 214 μg/m^3, was almost ten times higher than all mentioned standards. Plastic melting has been estimated to contribute 13.4% of $PM_{2.5}$ in Delhi, India and 6.8% of $PM_{2.5}$ in Nanjing, China (Islam et al., 2022). Cruz et al. (2023) rendered that the average amount of plastic waste that would have been burned per person per day was $2.66 \cdot 10^{-2} \pm 1.32 \cdot 10^{-2}$ kg in Guatemala, which generated $1.61 \cdot 10^7$ kg per year for $PM_{2.5}$. In Guatemala, ambient $PM_{2.5}$ exposure is estimated to result in 4105 annual deaths and 1.4 billion USD in health damages annually (WHO, 2021b). Therefore, high concerns about reducing the $PM_{2.5}$ in the atmosphere via better air filtration devices or applying suitable personal protection devices are critical to implementing in the studied factory. One thing should be noted that the $PM_{2.5}$ inside the house was even higher than in the other factories such as ABS, PET…(see *Table 2*). The possible explanation is that the house was downwind from the main recycling facility, especially the HDPE factory with its high $PM_{2.5}$ emissions, it would be directly exposed to airborne pollutants. Additionally, the house may have poor ventilation, leading to pollutant trap after entering from outside longer. Without proper air circulation, these particles could accumulate over time, leading to higher indoor concentrations.

The fumes from plastic melting normally release volatile compounds (VOCs), polychlorinated biphenyls (PCBs), polyvinyl chloride, dioxins, furans, CO, and CO_2 from the incinerator depending on the type of waste (Huang et al., 2013; Nagy and Kuti, 2016). Research by Huang et al. (2013) reported that the concentration of VOCs inside the plastic recycling plant reached values from 357.7–390.2 μg/m^3, while the environment outside the factory had VOCs concentrations from 314.0–329.4 μg/m^3, at the quality monitoring point about 20 km from the factories, the VOCs concentration was 282.4 μg/m^3. It was the somewhat similar to this study, in which the VOCs concentrations of 730 μg/m^3, 560 μg/m^3 and 200 μg/m^3 were obtained inside the factory, 100m and 200m outside the factory along the main wind direction, respectively. With the limit value of 500 μg/m^3 according to US EPA, the areas within radius of 100m were suffering from polluted air with VOCs.

Fuller et al. (2020) conducted an analysis of volatile compounds of recycled plastic resins sourced from a local plastic recycler. They rendered that three volatile compounds, i.e., 2,4-dimethyl-heptane, 4-methyl-octane and octamethylcyclotetrasiloxane, were found to be significantly related to the odor. 2,4-dimethyl-heptane has a strong, pungent plastic smell and is considered to be a major cause of the odor. 4-methyl-octane is highly correlated to 2,4-dimethyl-heptane and also contributes to the odor. The two alkanes may come from polymer degradation. Even though, there were not detailed VOC compounds analyzed in our results, the bad odor indicated that such volatile compounds, i.e., 2,4-dimethyl-heptane, 4-methyl-octane and octamethylcyclotetrasiloxane were possibly present at the studied factory

Risk assessment and reduction strategies

A comprehensive analysis of the risks associated with the pollutants is present in *Table 4*. The column “pollutant risk value” was the summation of the risk assessed for pollutants from sampling locations. Each location was assessed in terms of ‘1’ *little to no risk*, ‘2’ *non-hazardous and enforced, some risk* and ‘3’ *hazardous*, *high risk*. A value of ‘1’ in “Toxicity” means that the pollutant is hazardous, while a value of ‘0’ means that the pollutant is not. The column “regulation status” indicates whether the pollutant is enforced within Vietnam. Again, a value of ‘1’ means that the pollutant is hazardous, while a value of ‘0’ means that the pollutant is not dangerous. The column “factor of exceedance” refers to how significantly the pollutants found exceed the worldwide standard. Subsequently, the value of ‘2’ denotes a major exceedance, ‘1’ denotes somewhat of an exceedance and ‘0’ denotes little to no exceedance. The column ‘total summation’ is a final weighting from all the above-mentioned factors. This allows for a final decision based on the risk factor. Lastly, the column ‘ranking’ ranks the pollutants from most harmful to the least harmful. It should be noted that some of the pollutants share the same final rating and are subsequently given an equal rank.

From *Table 4*, it can be observed that the pollutants of concern based on their risks are in the following order: $PM_{2.5}$ > VOCs > PM_{10}, SO_2 and Ni > Cd > Pb > NO_2 and As. Thus, the solutions for reducing the emission of $PM_{2.5}$ and VOCs should be in the priority in remedy actions for supporting the craft village, in general, and the studied facility, in particular.

A risk weighting analysis was further undertaken, where each hazard generated from plastic recycling activities was assessed upon the likelihood of occurrence and impacts. The final score is a numerical score for each risk as mentioned in *Eq (1)*. Details on calculation method for Risk assessment can be seen in the risk assessment in the previous section. This aids in final recommendations as it allows targeted actions and a priority list for the actions implemented at the factory to increase health and safety. Based on the nature of activities at factories and the *formula (1)*, the risk score for the studied recycling factory was calculated as in *Table 5*.

Table 4. *Pollutants of concern*

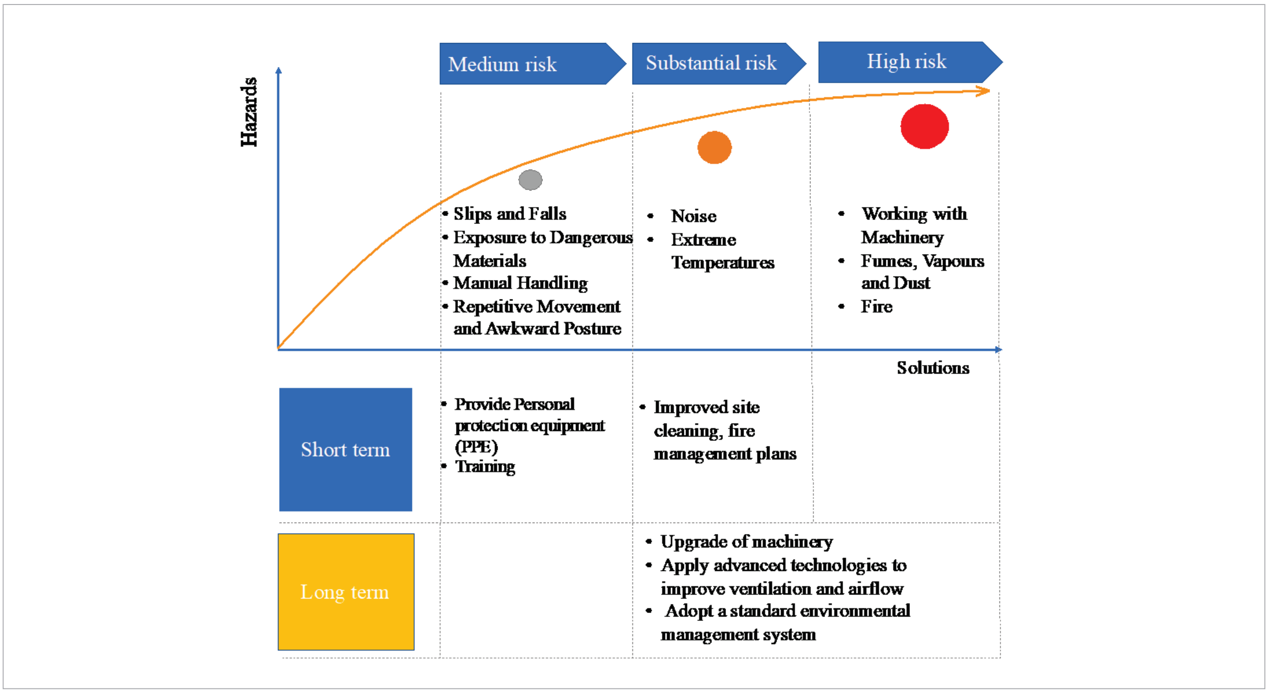
Parameter	Pollutant risk value	Toxicity	Regulation status	Factor of exceedance	Total summation	Ranking
PM_{10}	13	1	0	2	16	*3rd*
$PM_{2.5}$	17	1	0	2	20	*1st*
NO_2	12	1	0	0	13	*6th*
SO_2	14	1	0	1	16	*3rd*
Cd	12	1	1	1	15	*4th*
As	10	1	1	1	13	*6th*
Ni	14	1	0	1	16	*3rd*
Pb	12	1	0	1	14	*5th*
VOCs	16	1	0	2	19	*2nd*

Table 5. *Risk score calculation and risk reduction strategy for the studied facility*

Hazard	Consequence	Exposure	Probability	Score
Noise	Serious; permanent disability (15)	Continuously (10)	Would be a remotely possible coincidence (1)	150 (Substantial risk)
Working with Machinery, Mechanical	Serious; permanent disability (15)	Continuously (10)	Would be an unusual sequence or coincidence (3)	450 (High risk)
Slips, Trips and Falls	Minor; minor cuts, bruises, burns (1)	Continuously (10)	Quite possible / not unusual (6)	60 (Medium risk)
Fumes, Vapours and Dust	Serious; permanent disability (15)	Continuously (10)	Would be an unusual sequence or coincidence (3)	450 (High risk)
Exposure to Dangerous Materials (i.e., Chemicals)	Moderate; serious but non-permanent disability (5)	Frequently (once daily) (6)	Would be an unusual sequence or coincidence (3)	90 (Medium risk)
Manual Handling	Moderate; serious but non-permanent disability (5)	Frequently (once daily) (6)	Would be an unusual sequence or coincidence (3)	90 (Medium risk)
Fire	Disaster; multiple fatalities (50)	Rarely (once every 2–4 years) (1)	Quite possible / not unusual (6)	300 (High risk)
Extreme Temperatures	Moderate; serious but non-permanent disability (5)	Continuously (10)	unusual sequence or coincidence (3)	150 (Substantial risk)
Repetitive Movement and Awkward Posture	Minor; minor cuts, bruises, burns (1)	Continuously (10)	Quite possible / not unusual (6)	60 (Medium risk)

As seen in the *Table 5* all hazards varied from medium to high-risk scores. This is of concerns as there are limited controls in place to reduce the risk associated with each hazard. Some activities were at medium risks including slips or falls inside the working place, exposure chemicals, awkward and repetitive movement. While some were at high risks such as fire potential, dust, fumes or accidents with machinery. The recommendations should be a combination of both short-term immediate actions as well as long-term future actions that can be taken (*Fig. 4*). The short-term recommendations are based on training, setting realistic targets, and provide sufficient personal protection equipment (PPE). While the long-term recommendations are based on adopting an environmental management system as well as implementing new technologies to improve the efficiency of the factory's operations. These include the implementation of renewable energy (solar panels), industrial dust collection systems (e.g. shaker dust collectors, pulse jet dust collectors, cartridge collectors, cyclone dust collectors and electrostatic precipitators (Zaman, 2020) and retrofitting/upgrading systems/machinery used in the factories.

Fig. 4 *Short term and long term risk reduction strategies*



Conclusions

A thorough investigation in terms of water, wastewater and air quality analysis was implemented at the largest plastic recycling facility in a craft village in Vietnam. The initial results revealed that the groundwater quality was not affected by the recycling activities. The wastewater contained high concentration of COD, SS and coliforms, which were 5–10 times higher than the national and international regulations, thus, they should be treated carefully before discharging to the municipal sewer. Heavy metal concentrations were found under the acceptable values in both wastewater and air samples. For the air quality, PM10, PM2.5, noise and VOCs were of the most concerns in the HDPE, PP factory where all the plastic recycling activities (plastic washing, melting and granulation) occurred. The risk assessment eventually confirmed the pollutants and factories of concern so that proper mitigation solutions can be proposed in short and long terms. Furthermore, a more sustainable vision could be made with a roadmap to relocate polluting businesses to a designated industrial zone having a centralized wastewater treatment plant and proper air filtration systems.

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