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Soil heavy metal pollution from waste electrical and electronic equipment of repair and junk shops in southern Thailand and their ecological risk

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ABSTRACT

The waste electrical and electronic equipment (WEEE) stream in Thailand shifted from exporting WEEE to recycling them in domestic enterprises after China's import restrictions on e-waste in 2018. This study aims to investigate the pollution status, pollution sources, and ecological risk of heavy metals from manual WEEE dismantling facilities (12 repair shops and 8 junk shops) in the Nakhon Si Thammarat province of southern Thailand by examining the concentrations of As, Cd, Ni, and Pb in the topsoil (0–15 cm) during the wet and dry seasons. The results revealed that the mean concentrations of all heavy metals were higher during the dry season than in the wet season. The concentrations of analyzed soil heavy metals decreased as the intensity of e-waste dismantling activities increased, with recycling sites > repair sites > control sites (no e-waste recycling activities). Only 10% of WEEE processing workshops (junk shops) had soil Pb and As concentrations that exceeded Thailand's residential soil quality standards. However, ecological indexing models based on the geo-accumulation index found that 75% of electric repair shops were contaminated with the analyzed heavy metals, particularly Pb. Moreover, the Nemerow integrated pollution index indicated that 16.7% of electric repair shops were on the pollution warning line. Our findings suggest that policymakers should promote ecological risk assessment as a method for mitigating the negative environmental impact of electronic repair businesses, which are widely dispersed in residential areas and tend to dominate the WEEE stream because of the circular economy concept of "right to repair", and highlight the decline of junk shops and e-waste dismantling villages for waste export resulting from China's ban.

1. Introduction

Waste electrical and electronic equipment (WEEE), also known as e-waste, is an emerging global scale waste stream resulting from the increasing use of electronic items and their diminishing lifespan [1]. The global amount of WEEE has been estimated to increase from 75 million metric tons (Mt) by 2030 to 111 million Mt by 2050 [2]. Consequently, global WEEE generation has been increasing

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annually by 2 Mt (or approximately 3–4%); this problem is attributed to higher electronic consumption rates, shorter product lifespans, and limited repair options [3,4]. According to a study conducted by the United Nations University, Asia produces most of the world's WEEE, which was 18.2 million Mt in 2016, or 40.7% of the worldwide total [5]. Compared with Europe (35%), only 15% of Asia's WEEE is collected and recycled [5]. According to the United Nations Environment Program, 70% of all WEEE in 2012 ended up in China's "world factory" [6,7]. However, since 2018, the "China Ban" or "China Shock" has become a driving force for global WEEE recycling [8]. Therefore, the proper monitoring of WEEE flows due to the China ban is imperative at the global and regional levels.

WEEE contain valuable materials for industry (precious metals and copper) and recycling (metals and plastics) enterprises that can be used to alleviate depleting virgin natural resources [9]. However, despite the availability of recycling technology, recycling WEEE material does not often have economic incentive, and most studies have indicated that recycled e-waste sites are performed in rudimentary settings that may pose environmental risks [10–12].

A recent report by the Food and Agriculture Organization of The United Nations and the Intergovernmental Technical Panel on Soils concluded that the majority of the world's soil resources are only in fair condition at best, with 33% of the land resources being moderately to highly degraded [13]. Anthropogenic activities, such as informal WEEE recycling activities (burning, dismantling, and repair), contribute to high heavy metal concentrations in soils [14]. Currently, illegal WEEE trade from developed countries to developing counties poses serious challenges in terms of pollution from hazardous material transportation [1]. The informal sectors, which use polluting recycling methods to separate of reusable components and rapidly recovery its contained metals, play a key role in the recycling and management of WEEE streams in low-income countries that lack formal WEEE management services supported by adequate legislation. Even though the level of soil heavy metals at informal e-waste processing sites in developing counties is below the standard value, safe soil is not guaranteed. Ecological risk indices are policy-making tools that enable efficient WEEE management. Several classical techniques and empirical (numerical) models, such as the geoaccumulation index (I_{geo}), pollution index (PI), Nemerow integrated pollution index (NIPI), pollution load index, enrichment factor, contamination factor, contamination degree, and ecological risk index, can be used to evaluate the degree of contaminated soil at WEEE processing sites [15–19].

Circular economy concepts have been utilized in the recovery of resources from landfills and reduction of environmental problems caused by WEEE mismanagement. Four non-governmental organizations and representatives of waste treatment operators called for a revision of the European Union (EU) legislation on WEEE [20]. The WEEE regulation stipulates that electrical and electronic equipment (EEE) must be designed such that spare parts can be easily removed and replaced and general reparability can be enhanced. Moreover, the "right to repair" must include open access to repair information and spare parts for all repair companies as well as consumers. In addition, the ongoing COVID-19 pandemic has had a significant influence on consumer electronics [21]. Declining disposable income reduced the sales of non-essential electronics products and boosted the demand for electronic device repair services, and used EEE (UEEE). Repairing and reusing electronics is a desirable mainstream option because of the economic barrier that prevents many users from buying new items. The rising prominence of refurbished businesses for electronic devices may be one of the major factors fostering electronic equipment repair service market trends. Unfortunately, these activities are conducted under rudimentary conditions, which may pose risks to the environment due to the lack of emission control regulations and the operation of recycling activities without a license or authorization.

Data on the concentrations of heavy metals and their distribution patterns at various e-waste repair shops in countries where China prohibits waste imports have been limited. The soil status and ecological risk of dispersion sources close to residential settling, such as repair and junk shops, have received less attention. Thailand is a developing country that has been facing e-waste problems owing to the lack of technology, facilities, and resources, and gaps in e-waste regulations, resulting in improper or unsafe e-waste dismantling and recycling [22]. The informal sector, a key e-waste player in Thailand, is likely to distribute heavy metals and other toxic substances contained in e-waste. Due to the enforceability of China's 2018 ban on waste imports, which has resulted in a shift in Thailand from exporting WEEE to recycling domestically, economic problems caused by the Covid-19 pandemic, lack of WEEE regulation and regional monitoring of WEEE flows, increased WEEE quantity; and management changes, the possible sources of the contaminants and pollutants associated with WEEE processing and their associated ecological risks must be examined. This study assumes that the disassembly and recycling procedures in repair and junk shops constitute the majority of Thailand's WEEE stream. The monitoring of new e-waste recycling collectors, which operate without any registrations or permits to control the environmental impact from disassembly and repair activities, has been lacking. Furthermore, the majority of repair shops and service centers are located in residential neighborhood areas. Two ecological indexing models, the NIPI and I_{geo}, were used to assess the state of heavy metal pollution caused by China's ban in the Nakhon Si Thammarat province of southern Thailand. The results of the study will assist policymakers in identifying WEEE sources, particularly in the repair sector, which have emerging contaminant spread and play a role in characterizing contaminated soils. Our results also have implications for remediation efforts.

2. Materials and methods

2.1. Research area

The sites considered for this study are located in Nakhon Si Thammarat, one of the top 10 provinces in southern Thailand, with the most severe solid waste management challenges [23]. The city experiences humid and tropical monsoons, with an average annual temperature of 27.7 °C and average precipitation of 491.9 mm (wet season), and 113.0 mm (dry season) [24]. Because the majority of electrical distributors/service centers, repair shops, and junk shops are located in major cities, two sampling districts in Nakhon Si Thammarat province were selected: Mueang Nakhon Si Thammarat (8°25′49.46″N, 99°57′47.29″E), the representative urban area, and the Tha Sala districts (8°39′54.13″N, 99°55′20.92″E), the representative rural area. The study was designed such that the sampling location and size were representative of the e-waste recycling pollution sources and status changes that were impact by China's import prohibition in 2018. The workshops for recycling e-waste were categorized as (i) 12 electronic repair workshops (R1−R12, locations for representative disassembly and repair activities), (ii) 8 junk shops (J1−J8, locations for representative burning, dismantling/-recycling activities) and (iii) reference site (C1–C2, pristine agricultural land located more than 5 km away from the abandoned e-waste repair and junk shop sites).

2.2. Data collection

Comprehensive and structured WEEE-related questionnaires were designed and administered to various repair and junk shop owners in 20 survey areas of the Tha Sala and Mueang Nakhon Si Thammarat districts. The survey questions were answered through in-person interviews with shop owners. Questionnaires were used to identify the current flow and disposal of WEEE in the repair and recycling sectors. In particular, household electronic appliances were the WEEE for which the data collection was intended.

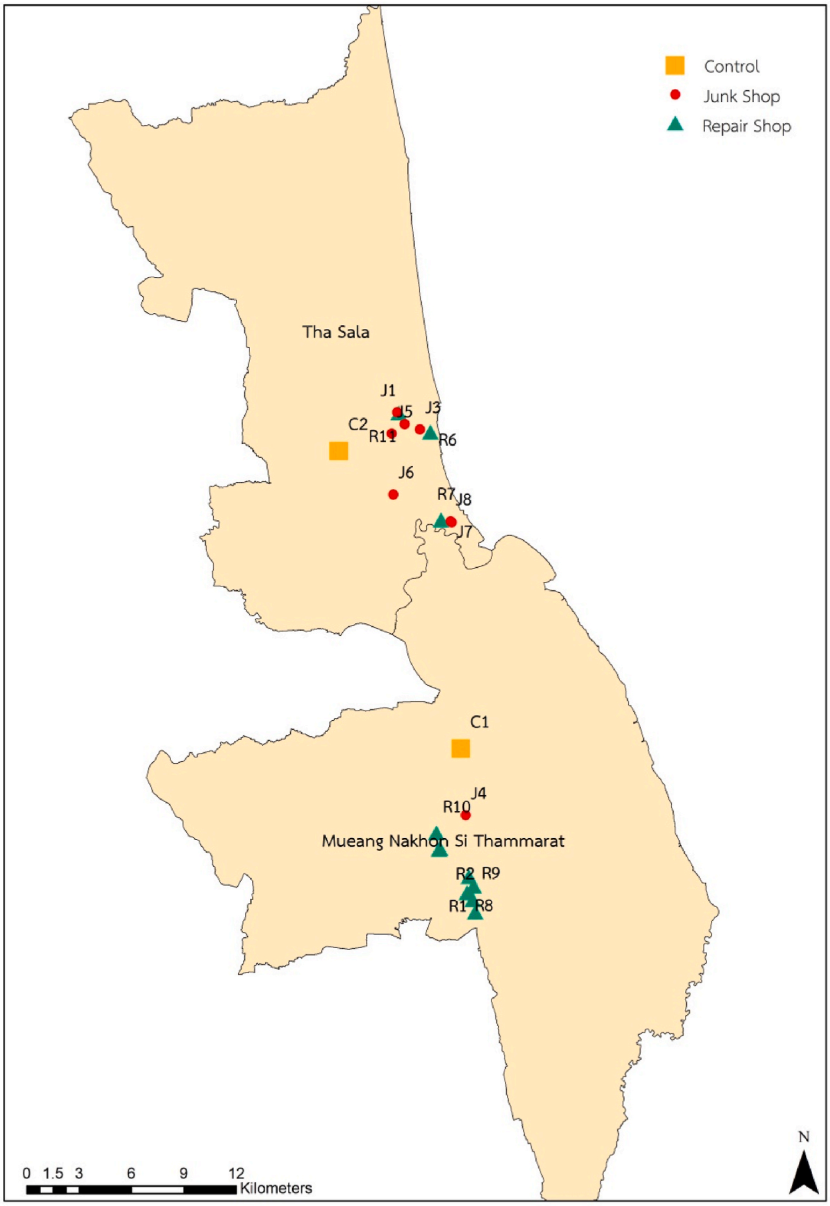

Fig. 1. Map of Nakhon Si Thammarat showing the research locations.

2.3. Soil sample collection and preparation

A total of 84 soil samples were collected from 20 e-waste processing workshops and two reference sites in the Muenag Nakhon Si Thammarat and Tha Sala districts in Nakhon Si Thammarat. The sampling points are shown in Fig. 1. In total, 180 topsoil (0–15 cm) samples were collected during the wet season in December 2019 and the dry season in August 2020. To determine the level of pollution caused by recycling-related e-waste workshop operations, soil sample points were placed as close as possible to e-waste processing activities, such as the burning of cables and disintegration of cathode-ray tube (CRT) glass (dismantling, repairing, recycling). Homogenized composite samples were air-dried, crushed, and sieved through a 2 mm mesh. The samples were held in polyethylene bags at 20 °C at the Center for Scientific and Technological Equipment at Walailak University until analyses were conducted.

In this study, trace metals were extracted using the digestion process developed by Francek et al. [25]. The soil was crushed, weighed (1 g), and digested with 10 ml of 1:1 concentrated HNO_3. The mixture was evaporated to near dryness on a hot plate and cooled, and the procedure was repeated using 1:1 concentrated HCl (15 ml). The extracts were filtered using No. 40 Whatman filter paper and then brought up to a volume of 100 ml with 2% HNO_3. Digestion was performed in triplicate for all analyses. The presence of heavy metals (As, Cd, Ni, and Pb) in the soil samples was determined using inductively coupled plasma optical emission spectrometry (ICP-OES, Avi 500, PerkinElmer Instruments, USA).

2.4. Determination of heavy metal contamination in soil

To obtain a more comprehensive understanding of the heavy metal pollution levels in the soils near WEEE recycling workshops, this study incorporated two widely used numerical models, the single index I_{geo} and combined index NIPI, for the assessment of heavy metal pollution in soils [26]. The evaluation equation models and classification schemes used for the soil quality matrices are presented in Table 1.

3. Results and discussion

3.1. Role of repair business and junk shops in the EEE life cycle

Thailand has a variety of household e-waste recycling business types. In this study, e-waste recycling collector refers to two business types: EEE repair businesses (involving various types of consumer electronics that can be repaired or resold for profit) and junk shops (involving WEEE types that cannot be repaired, e.g., broken WEEE). Informal e-waste collectors typically include waste pickers, landfill pickers, junk merchants, house dismantlers, tricycle drivers, garbage collectors, and scrap dealers. This study identifies three distinct types of businesses related to e-waste collection, disassembly, and recycling (none of which had a particular license for e-waste recycling) that engage in dismantling (Table 2): (i) small repair and second-hand stores (50%), (ii) junk shops with e-waste dismantling activities (40%), and (iii) large dealer and repair shops (10%). According to the survey, there are more small repair shops (83.3%), which are scattered across the community and residential areas, than dealer repair shops (16.7%). Due to the lack of technology and operational capacity in small repair shops, the repair processes of EEE household appliances (i.e., televisions, air conditioners, refrigerators, and washing machines) are performed manually without the use of modern technology. In addition, some repairers have never attended college or vocational school to gain technical expertise. According to the findings, only 25% of repair shop owners in this study had more than ten years of experience working as repairers in large EEE firms (Table 2).

Disassembly is a common activity in both repair and junk shops. Typically, disassembly involves defective or non-functional UEEE and requires the repair or extraction of reusable pieces for recovery or sale on demand. Typically, the owner of a junk shop purchases recyclable e-waste from home waste collectors and dismantlers, separates them, and then either stores or sale them to clients (domestic and external) or exports it to China. According to discussions with the owners of junk shops, these businesses related to e-waste collection, disassembly, and recycling are currently under pressure because of China's import restrictions and the decline in WEEE selling prices, which has led some junk shop owners to decide to close their operations in the near future. This is comparable to the

Table 1
Pollution risk classification of soils based on the two pollution assessment models.

Model name	Equation	Explanations	Soil pollution risk classifications	References
Geoaccumulation index	$I_{geo} = \mathrm{Log}_2\frac{C_{HMS}}{1.5 \times GBV}$	C_{HMS} = concentration of heavy metals in soils; GBV = geochemical background value. The constant 1.5 allows to analyses natural fluctuations in the content of a given substance in the environment	uncontaminated ($I_{geo} \le 0$); uncontaminated to moderately contaminated ($0 < I_{geo} \le 1$); moderately contaminated ($1 < I_{geo} \le 2$); moderately to heavily contaminated ($2 < I_{geo} \le 3$); heavily contaminated ($3 < I_{geo}o \le 4$); heavily to extremely contaminated ($4 < I_{geo} \le 5$); extremely contaminated ($I_{geo} \ge 5$)	[27–29]
Nemerow integrated pollution index	$P_N = \sqrt{\left(\frac{{P_{max}}^2 + {P_{avg}}^2}{2}\right)}$	P_N = Nemerow's pollution index P_{max} = the maximum single pollution index among the pollutants P_{avg} = the average mean of single pollution indexes among the pollutants	no pollution (NIPI ≤0.7); warning line of pollution (0.7 < NIPI ≤1); low level of pollution (1 < NIPI ≤2); moderate level of pollution (2 < NIPI ≤3); high level of pollution (NIPI >3)	[30,31]

Table 2
Characteristics of WEEE shop owners.

Characteristic	Count	Percent
Sex		
Male	15	75
Female	5	25
Education level		
Primary school	4	20
Junior high school	3	15
Senior high school or vocational	2	10
Diploma or high vocational	6	30
Bachelor's degree	5	25
Experience in WEEE recycling (yr)		
< 5	2	10
5–10	5	25
11–15	4	20
16–20	5	25
> 20	4	20
Business class		
Small repair and second-hand shop (used EEE)	10	50
Junk shops with e-waste dismantling operation	8	40
Large dealer and service center	2	10
Type of permit		
License for auction and used goods trading	8	40
Certificate of commercial/business registration	4	20
No certificate	2	10
Not reported	6	30

report of Thai customs trade statistics, which state that Thailand exported ≥80% of its plastic waste to China in 2013, but this amount decreased to 14.2% in 2018 [32]. This may result in the loss of junk shops and e-waste dismantling villages in Thailand because of a lack of demand for recycled material exports, and the repair sector may become the primary source of household WEEE recycling streams in the future as a result of household consumption and demand for UEEE among those unable to afford new EEE.

This study also determined a summary of the business practices utilized by EEE repair businesses. First, manual testing is used to identify defective or broken EEE/UEEE components, as well as useable pieces (spare parts) that can be resold to other customers. Malfunctioning components are removed, replaced, and then reassembled. If useable components are found during the disassembly process, they may be joined with other components to form a more acceptable functional set.

Multiple functions and activities, including selling, repairing, disassembling, and refurbishing are typical of the EEE repair shops and were examined in this study. All EEE repair shops sell both new and UEEE, but use a few different methods. First, the proprietor of a repair shop may purchase defective or nonfunctioning EEE (particularly UEEE) from a local user, and then repair and resell the item. Second, the proprietor of the repair shop might purchase UEEE from a local user at a reduced price, refurbish it, and sell it to the next consumer at the negotiated price. Third, the repairer merely repairs a malfunctioning or nonfunctioning EEE upon the user's request. Because purchasing UEEE is less expensive than purchasing new EEE, the repair sector may plays a significant role in WEEE recycling, and e-waste flow may gain momentum as a result.

3.2. Quantity and composition of WEEE streams in repair and junk shops

End-of-life management of WEEE in Thailand has been dominated by the informal sector, which comprises a myriad of small repair workshops, retailers, and junk shops. In general, post-consumer waste flows through three different channels: i) donation or sale to repair shops, ii) sale for recycling, and iii) disposal as waste [33]. In this study's e-waste stream, repair businesses accounted for approximately 24.3% of the total e-waste collected. Home appliance products such as televisions (25%), air conditioners (20%), washing machines (12%), and refrigerators (11%) were the fastest-growing obsolete products in the stream of e-waste from repair and junk shops (Table 3). According to the Directive 2012/19/EU in Annex III, the temperature exchange equipment (category 1) accounted for 31% of all e-waste generated by repair and junk shop enterprises, followed by screens, monitors, and equipment containing screens having a surface greater than 100 cm^2 (category 2, 25%), small equipment (category 5, 23%), large equipment (category 4, 12%), and small information technology and telecommunication equipment (category 6, 9%).

Typically, e-waste contains valuable and potentially toxic components that require careful handling [34]. The recycling of WEEE for both repair and junk shops begins with sorting and manual dismantling into recyclable and undesirable materials (Table 4). Steel, copper, aluminum, recyclable plastic, and circuit boards are examples of valuable materials; however, non-recyclable plastic, polyurethane foam, and glass are undesirable remnants of disassembly activities in repair and junk shops. Examples of manual dismantling procedures include: (i) physical dismantling objects using tools such as hammers, chisels, screw drivers, and bare hands to separate various materials; this includes breaking CRT glass and releasing refrigerant; (ii) chipping and melting plastics without adequate ventilation; and (iii) burning undesirable materials such as printed circuit boards, cables, and wires outside to recover valuable metals.

Backyard operations consist of disassembly, metal recycling, and recovery via manual techniques, and rudimentary processes. Remnants of recycled e-waste materials are discarded on the ground in the area of their stores. Because the majority of repair shop

Table 3
Type and amount of e-waste.

Sampling site	Type of WEEE (monthly average unit)											Number of items disassembled
	Category 1		Category 2	Category 4	Category 5				Category 6			
	Air conditioners	Refrigerator	Television	Washing machines	Fan	Radio	Vacuum cleaner	Iron	Scanner	Mobile phone/ phone	Computer	
R1[e]	0	1	120	60	120	1	1	2	0	0	1	0
R2	10	25	0	10	0	0	0	0	0	0	0	45
R3	2	6	0	4	0	0	0	0	0	0	0	12
R4[e]	60	0	0	0	0	0	0	0	0	0	0	0
R5	0	5	3[a]	5	0	0	0	0	0	0	0	13
R6	0	3	3[a]	2	0	0	0	0	0	0	0	8
R7	0	0	10[a]	3	0	1	1	1	0	0	0	16
R8[e]	15	20	0	30	0	0	10	10	10	15	0	0
R9[e]	70	10	0	10	0	0	0	0	0	0	0	0
R10[e]	25	20	15[a]	10	0	0	5	0	0	0	0	0
R11	10	20	20[a]	30	0	0	5	0	0	0	0	85
R12	3	1	5[a], 20[b]	3	0	2	0	0	0	0	0	34
J1	30	3	4[b]	0	0	5	0	0	0	0	0	42
J2	1	3	10[a]	3	0	0	3	20	10	15	4	69
J3	30	5	4	0	0	5	0	0	0	0	0	44
J4	1	6	50[a], 6[b, e]	3	0	0	10	100	10	40	4	230
J5	0	0	30[a]	0	0	0	0	0	0	0	0	30
J6	15	6	17[a], 3[b]	7	0	7	3	20	6	10	6[c], 3[d]	103
J7	1	30	60[a]	5	0	0	0	0	0	0	0	96
J8	30	3	4	0	0	5	0	3[e]	5	0	0	47
Sum repair shop	195	111	196	167	120	4	22	13	10	15	1	213
% Repair shop	23	13	23	20	14	0	3	2	1	2	0	–
Sum junk shop	108	56	188	18	0	22	16	140	31	65	17	661
% Junk shop	16	8	28	3	0	3	2	21	5	10	3	–
Sum total shop	303	167	384	185	120	26	38	153	41	80	18	874
% Total shop	20	11	25	12	8	2	3	10	3	5	1	–

[a] CRT Television.
[b] LCD Television.
[c] Screen.
[d] CPU.
[e] not disassembly.

Table 4
General dismantled e-waste components generated from the repair shops and junk shops.

Item	Dismantled e-waste components per month
Valuable material	Steel: Avg. = 10,750 kg (SD = 2,986 kg), Range 8,000 − 15,000 kg Copper: Avg. = 1,172 kg (SD = 2,159 kg), Range 8 − 5,000 kg Aluminum: Avg. = 1,301 kg (SD = 2,104 kg), Range 5 − 5,000 kg Recyclable plastic: Avg. = 3,620 kg (SD = 3,824 kg), Range 100 − 10,000 kg Circuit boards and cables can be disposed of in a variety of ways, including burning, wire stripping, or resale without disassembly. Refrigerant R32: store in a tank container and sell
Unwanted material	Non-recyclable plastic: Avg. = 3,025 kg (SD = 4,207 kg), Range 50 − 6,000 kg PUR refrigerator foam: Avg. = 16 kg (SD = 2 kg), Range 4 − 60 kg (2 kg/unit) Glass: break CRT glass to obtain valuable metals from televisions or computer monitors Refrigerant R32 can be disposed of in several ways, including through a discharge line to a sewer pipe, discharge to ambient air, or collecting for disposal at an open dumping site

buildings are shop houses, disassembly and repair practices are often undertaken indoors. Heavy metal-containing dust is likely transmitted from the indoor floor dust of repair shops to the topsoil in their immediate vicinity. As a result of China's ban, these data suggest that the levels of heavy metals in repair businesses must be monitors, especially for buildings scattered among residential and community areas.

3.3. *Contamination levels of heavy metals in soil samples*

Table 5 describes the mean concentrations of heavy metals (As, Cd, Ni, and Pb) in the topsoil of shops conducting WEEE dismantling activities during the wet and dry seasons. The concentrations of all heavy metals were higher in the dry season than in the wet season. This is consistent with the results of previous studies [35]. The average soil levels of As, Cd, Ni, and Pb in the wet and dry seasons were 1.936, 0.131, 2.870, and 67.900, and 3.409, 0.318, 5.495, and 89.195 mg/kg, respectively. Several climatic and environmental factors, which can differ between dry and wet seasons, can influence the concentration of heavy metals in the soil of repair and junk shops. Leaching, precipitation, soil erosion, and water level variations during the wet season can redistribute heavy metals in the soil [36,37]. During the wet season, precipitation leaches the heavy metals from the soil, resulting in a decrease in heavy metal

Table 5
Concentration of heavy metals in topsoil samples collected from the dismantling e-waste processing shops.

Shop	Heavy metal (mg/kg)							
	Wet season (December 2019)				Dry season (August 2020)			
	As	Cd	Ni	Pb	As	Cd	Ni	Pb
R1	0.229	0.020	0.718	4.709	0.906	0.450	1.526	10.050
R2	0.938	0.140	2.656	28.291	1.682	0.578	8.980	46.350
R3	0.297	0.139	2.945	54.975	0.317	0.200	3.878	69.190
R4	1.051	0.040	1.615	1.072	1.895	0.077	3.098	2.507
R5	0.338	0.081	1.656	15.291	0.659	0.131	2.322	19.650
R6	0.279	0.051	0.478	2.895	1.219	0.067	0.887	3.309
R7	0.299	0.020	0.778	5.277	0.816	0.047	0.980	8.086
R8	0.956	0.110	1.560	19.125	1.149	0.128	1.770	24.960
R9	0.177	0.021	0.476	3.255	0.328	0.134	0.681	3.902
R10	0.740	0.020	4.811	3.845	0.950	0.032	4.503	11.940
R11	1.235	0.027	0.267	2.185	1.785	0.682	0.303	10.230
R12	0.245	0.024	0.217	2.410	0.522	0.550	0.375	4.363
J1	1.745	0.218	4.561	25.521	2.292	0.257	6.230	25.860
J2	1.652	0.060	0.837	4.479	1.317	0.049	0.593	4.598
J3	0.817	0.020	1.061	3.485	1.498	0.045	0.998	3.261
J4	21.051	0.945	4.615	575.210	41.740	1.836	9.168	768.800
J5	3.876	0.109	0.734	1.922	5.057	0.176	0.837	2.005
J6	1.214	0.110	8.400	346.300	1.596	0.260	14.370	497.400
J7	1.125	0.318	18.561	255.210	1.745	0.521	47.730	263.500
J8	0.456	0.145	0.452	2.543	0.700	0.138	0.666	3.941
C1	0.129	0.015	0.167	1.009	0.256	0.022	0.167	1.150
C2	0.147	0.023	0.153	1.067	0.344	0.012	0.213	1.210
Avg. (Repair shop)	0.565 ±0.387	0.058 ±0.047	1.515 ±1.376	11.944 ±15.971	1.019 ±0.544	0.256 ±0.238	2.442 ±2.473	17.878 ±20.392
Avg. (Junk shop)	3.992 ±6.970	0.241 ±0.299	4.903 ±6.181	151.834 ±217.843	6.993 ±14.101	0.410 ±0.596	10.074 ±16.027	196.171 ±292.953
Avg. (Total)	1.936 ±4.577	0.131 ±0.207	2.870 ±4.251	67.900 ±150.250	3.409 ±9.080	0.318 ±0.412	5.495 ±10.625	89.195 ±199.724
Standard (Thailand)[a]	6.0	67.0	436.5	400.0				

[a] Notification of the National Environmental Board: Soil quality standard for residential use, 2021 [40].

concentration. Soil moisture content can influence the availability of heavy metals in the soil for absorption by plants and other organisms. During the rainy season, the soil may contain more water, causing plants and organisms to absorb more heavy metals. In contrast, soil moisture content may be lower during the arid season, and evaporation is more intensive in the dry season, resulting in the decreased uptake of heavy metals by plants and organisms. Moreover, increased levels of dust deposition may contribute to the accumulation of heavy metals in the soil during the dry season. Dust may settle less during the wet season owing to precipitation, resulting in reduced heavy metal accumulation in the soil [38].

The variation in heavy metal concentrations decreased as follows: Pb > Ni > As > Cd. The high concentrations of lead in the junk shop dumps may be due to the disposal of cathode ray tubes, computer monitor glass, and printed wiring boards. Pb can remain in the air for 10 d before settling to the ground and contaminating adjacent water resources and soil [39]. During the dry season, the arsenic level of the soil ranged from 0.32 to 41.74 mg/kg, with an average of 3.41 mg/kg. Two junk shops have soil Pb (J4 and J6) and As (J4) concentrations that exceeded Thailand's residential soil quality standards [40] during the dry season.

Numerous studies on e-waste disassembly sites have revealed that the soil in developing countries is extensively exposed to a variety of toxic pollutants from recycling units [41–43]. The overall pattern of heavy metals was as follows: burning sites and dismantling sites (junk shops) > repair sites > control sites. The higher concentration of heavy metals in the soil at junk shops compared with repair shops is likely due to a combination of factors related to the age and condition of the electronic products being handled, type of activities occurring in each context, and location of the shops. One possible explanation is that junk stores frequently deal with obsolete or irreparable electronic devices, which may contain higher levels of heavy metals as a result of their age and use. Additionally, these products may be disassembled carelessly, resulting in the release of heavy metals into the environment. In contrast, repair businesses typically deal with functional electronic products that require some level of repair or maintenance. These items may be more recent, contain lower levels of heavy metals, and are typically handled with greater control and organization. Another factor that may contribute to the difference in heavy metal concentrations between junk and repair shops is the type of activities that occur in each setting. Junk shops could engage in activities such as the open burning of electronic waste, which can release heavy metals into the environment. In contrast, repair shops may be situated in commercial or residential locations with higher-quality soil and may engage in fewer activities that contribute to heavy metal contamination. A study conducted in China found that junk shops had higher concentrations of heavy metals in the soil than repair shops, and that the concentration of heavy metals was positively correlated with the age of the electronic products being handled [44]. Another study found that informal e-waste recycling activities, which frequently occur in junk shops, are associated with higher concentrations of heavy metals in the soil [45].

Even though the majority of shop-related e-waste processing has heavy metal concentrations that comply with Thailand's residential soil quality standards, the presence of more heavy metals in the topsoil of these shops compared with those in the control sites (undisturbed activity area) suggests that the dismantling process at the repair and junk shops may pollute the surrounding environment. Therefore, the study emphasized the recommendation for follow-up actions and surveillance of e-waste related shops located in the vicinity of residential building in exporting nations, such as Thailand, affected by China's e-waste prohibition.

3.4. Ecological risk assessment of heavy metal pollution from e-waste processing facilities

Tables 6 and 7 show the levels of heavy metal pollution in shop-related e-waste processing. The NIPI ranges for repair and junk shops are 0.059–0.835 and 0.06–3.596, respectively (Table 6). According to the NIPI classification, the majority of the studied soil samples from repair shops had a low level of contamination (NIPI <0.7). Nonetheless, two repair shops report a NIPI value in the

Table 6
NIPI of samples collected from shops.

Shop	P_i (As)	P_i (Cd)	P_i (Ni)	P_i (Pb)	P_N	Soil pollution risk classifications
R1	0.036	0.750	0.008	0.059	0.551	No pollution
R2	0.067	0.963	0.047	0.273	0.722	Warning line of pollution
R3	0.013	0.333	0.020	0.407	0.319	No pollution
R4	0.076	0.128	0.016	0.015	0.100	No pollution
R5	0.026	0.218	0.012	0.116	0.168	No pollution
R6	0.049	0.112	0.005	0.019	0.085	No pollution
R7	0.033	0.078	0.005	0.048	0.062	No pollution
R8	0.046	0.213	0.009	0.147	0.168	No pollution
R9	0.013	0.223	0.004	0.023	0.165	No pollution
R10	0.038	0.053	0.024	0.070	0.059	No pollution
R11	0.071	1.137	0.002	0.060	0.835	Warning line of pollution
R12	0.021	0.917	0.002	0.026	0.670	No pollution
J1	0.092	0.428	0.033	0.152	0.328	No pollution
J2	0.053	0.082	0.003	0.027	0.065	No pollution
J3	0.060	0.075	0.005	0.019	0.060	No pollution
J4	1.670	3.060	0.048	4.522	3.596	High level of pollution
J5	0.202	0.293	0.004	0.012	0.226	No pollution
J6	0.064	0.433	0.076	2.926	2.159	Moderate level of pollution
J7	0.070	0.868	0.251	1.550	1.198	Low level of pollution
J8	0.028	0.230	0.004	0.023	0.170	No pollution

P_i – Single Pollution Index; P_N – Nemerow Comprehensive Pollution Index.

Table 7
Calculated I_{geo} values for repair shops and junk shops.

Shop	I_{geo} values			
	As	Cd	Ni	Pb
R1	2.23 ++	4.64 ++++	2.61 ++	3.25 +++
R2	3.12 +++	5.01 +++++	5.16 +++++	5.46 +++++
R3	0.71 −+	3.47 +++	3.95 +++	6.04 +++++
R4	3.29 +++	2.10 ++	3.63 +++	1.25 +
R5	1.77 +	2.86 ++	3.21 +++	4.22 ++++
R6	2.66 ++	1.90 +	1.82 +	1.65 +
R7	2.08 ++	1.38 +	1.97 +	2.94 ++
R8	2.57 ++	2.83 ++	2.82 ++	4.57 ++++
R9	0.76 −+	2.90 ++	1.44 +	1.89 +
R10	2.30 ++	0.83 −+	4.17 ++++	3.50 +++
R11	3.21 +++	5.24 +++++	0.27 −+	3.28 +++
R12	1.43 +	4.93 ++++	0.58 −+	2.05 ++
J1	3.57 +++	3.84 +++	4.64 ++++	4.62 ++++
J2	2.77 ++	1.44 +	1.24 +	2.13 ++
J3	2.95 ++	1.32 +	1.99 +	1.63 +
J4	7.75 +++++	6.67 +++++	5.19 +++++	9.51 +++++
J5	4.71 ++++	3.29 +++	1.74 +	0.93 −+
J6	3.04 +++	3.85 +++	5.84 +++++	8.88 +++++
J7	3.17 +++	4.86 ++++	7.57 +++++	7.97 +++++
J8	1.86 +	2.94 ++	1.41 +	1.90 +

uncontaminated: −− uncontaminated to moderately contaminated, −+; moderately contaminated, +; moderately to heavily contaminated, ++; heavily contaminated, +++; heavily to extremely contaminated, ++++; extremely contaminated, +++++.

"Warning line of the pollution" risk status (R2 and R11).

In this study, the I_{geo} values for heavy metal contamination ranged from 0.27 to 9.51 (Table 7). Two repair shops (16.7%) and three junk shops (37.5%) were extremely contaminated with Pb. Shop J4 was extremely contaminated with all heavy metals. Among the 12 repair shops, shop R2 was extremely contaminated with Cd, Ni, and Pb, and heavily contaminated with As. The nickel contamination level was also extreme in one repair shop (R2) and three junk shops (J4, J6, and J7), whereas arsenic and cadmium contamination levels ranged from heavily to extremely contaminated. The Cd contamination level for repair shop R11 was also extremely high. However, the I_{geo} values for our e-waste dismantling shops were higher than those reported for other e-waste recycling sites worldwide [15,46] and also higher than those for separate households or residential areas [47]. In shop-related e-waste processing, particularly in nine recycling shops (75%), heavy to extreme levels of heavy metal contamination were found in the topsoil.

Globally, published data on heavy metals in soil from electronic repair workshops are limited. Despite the fact that the vast majority of repair and junk shops in the study area have soil heavy metals below the soil quality standard for residential use, the ecological risk in terms of NIPI and I_{geo} reveals that some residents of this metropolitan area are more likely to be exposed to ecological threats due to the presence of heavy metals in the soil in the vicinity of health-hazardous businesses such as repair and junk shops. In addition, this study provides rudimentary information for future strategy considerations regarding the mitigation of environmental contamination following China's ban.

Identifying the pollution status is an essential step in determining the potential effects of soil heavy metal pollution. However, various methods produced different results. Therefore, method selection should be one of the most important aspects of heavy metal evaluation. Based on Tables 6 and 7, polluted samples collected from junk shops assessed by the NIPI were consistent with I_{geo}. However, the degrees of pollution classified by I_{geo} were much more severe than those classified by NIPI for repair shops, indicating that I_{geo} may have overestimated heavy metal pollution in the topsoil of repair shops. These results indicated that heavy metal pollution might be overestimated for soils collected from repair shops using I_{geo}. In conclusion, the combined NIPI index is preferable to the single I_{geo} index when assessing heavy metal contamination in soil from dispersion sources close to residential areas, such as repair and junk shops.

3.5. Measures for health-hazardous businesses involving WEEE

Recycling activities are conducted based on the market force or business drive, and environmental protection measures are not implemented in many cases [48]. Soil heavy metal pollution is an environmental concern, particularly when e-waste is involved [49]. In this study, processing procedures such as the manual disassembly of cable and circuit boards, separation of metal and plastic, and sorting of electrical components are typically conducted in workshops located within or close to residential areas. The study revealed the presence of As, Ni, Cd, and Pb concentrations in the topsoil of business-related WEEE, including both junk and repair shops, with repair shops being mostly located in residential areas. Contaminated topsoil used for residential purposes can pose environmental and human health risks, particularly when vulnerable populations such as children and the elderly who live in close proximity to repair and junk shops are subjected to long-term exposure.

Increasing product lifespans is one of the most effective environmental strategies for mitigation soil heavy meal contamination. Therefore, the repair business is a component of the circular economy that aims to extend the use of UEEE [50]. Controlling the direct discharge of hazardous metals into the environment from the repair sector of buildings in residential areas is another method for minimizing the negative effects of soil pollution on the environment and human health [51]. Some nations have designed city plans that separate the residential and hazardous business areas. However, in a low-income country such as Thailand, where the same building is used for both living and working, implementing such measures seem impossible.

To decrease soil contamination by e-waste-derived heavy metals, our findings suggest that repair and junk shops should be registered as businesses hazardous to health, and outdoor dismantling should be prohibited. Additionally, the informal sector plays an important role in WEEE management; consequently, this sector should be considered in WEEE management. In addition to promoting responsibility and awareness of health-hazardous businesses, local government or environmental health management decisions should use the ecological risk index as a screening tool to propose adaptive management or follow-up measures to evaluate the risk predictions of businesses located near residential areas. These may include surveillance monitoring, adopted landscape-perspective assessments, and necessary regulations and policies for the protection of residents vulnerable to heavy metal exposure.

4. Conclusions

This study provides preliminary information on the soil pollution status of the informal e-waste related businesses in Nakhon Si Thammarat province, southern Thailand, in response to China's ban on e-waste. Some junk shops were found to have soil Pb and As concentrations that exceed Thailand's habitat soil quality standard, whereas the topsoil surrounding repair shops meet the standard. The average individual metal contents in the studied soil samples were ordered from high to low as follows: Pb > Ni > Cd > As. Based on the findings of this study, efforts to prevent or reduce heavy metal pollution in junk and repair shops must prioritize Pb contamination. Based on the evaluation of soil pollution indices, NIPI and I_{geo}, a considerable number of samples were contaminated by heavy metals in junk shops (37.5%) and repair shops (16.7%), and were classified above the warning line of pollution. These findings are relevant to land utilization and highlight that shops involved in e-waste repair, disassembly, and recycling activities, which are widely dispersed in residential areas, should be considered health-hazardous businesses and must have pollution monitoring policies that emphasize surveillance.

Managing e-waste in the informal sector is a problem, especially in developing countries that require immediate action. As emerging e-waste collectors, recyclers, and re-users, repair and junk shops must be involved in the management of the e-waste cycle. E-waste can be kept out of landfills by encouraging the reuse of components and equipment, increasing the recyclability of materials in repair shops, and promoting responsible mitigation among relevant e-waste stakeholders. Moreover, repair businesses should play a crucial initial role in preventing heavy metal emission from disassembly and repair activities as part of the "right to repair" concept of circular economies as extending product lifespans reduce heavy metal contamination. Repair processing procedures must be update with state-of-the-art and eco-friendly approaches to manage e-waste.

The ecological risk index can be used to identify potential hazards associated with the renewal of legal permission for health-hazardous businesses to continue operations. Based on the results of this study, the ecological risk index, particularly in terms of I_{geo} and NIPI, could be used to assess the level of heavy metal contamination in soil and serve a screening tool for determining the significance of WEEE sources. Because heavy metals in soils do not break down over time like organic matter does, they may accumulate and eventually exceed their allowable standards. This suggests that WEEE-related businesses located in close proximity to residential areas should regularly conduct ecological risks assessment to protect residents who are vulnerable to long-term heavy metal exposure.

For other developing countries with similar WEEE problems in terms of high levels of informal markets, value chain actors, including manufactures, marketers, customers, transporters, collectors, reconditioners, and recyclers, must participate in the collection, reconditioning, repair, and reuse of WEEE as part of the waste management chain and serve as feeders for the subsequent recycling and disposal route. The education sector, including vocational school or licensing/certification holders, should incorporate the sustainable management scheme of WEEE recycling and reuse during curriculum development.

Availability of data and material

Data will be made available on request. This research was approved by the human research ethics committee of Walailak University (no. WUEC-18-115-01).

Additional information

No additional information is available pertaining to this article.

CRediT authorship contribution statement

Siriuma Jawjit: Data curation, Investigation, Methodology, Visualization, Writing - original draft. **Supabhorn Yimthiang:** Data curation, Investigation, Writing – original draft. **Panatda Pibul:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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