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Research article

Transforming and integrating informal sectors into formal e-waste management system: A case study in Guiyu, China

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Abstract: Minimizing informal recycling activities is critical for the sustainable end-of-life treatment of electronics. Recent studies have started to revisit the concept of informality in recycling and reported empirical examples where informal sectors coordinate with formal sectors, jointly contributing to a greener recycling solution. This case study examines the systematic effort to transform and integrate the informal sector into the formal recycling industry for managing e-waste in Guiyu, China. This paper analyzes the policy design, implementation, technology development and market establishment of Guiyu's formal sector that enabled the evolution of the local informal recycling industry. The results show that the salient success factor is to offer advanced and centralized e-waste treatment by constructing a formal recycling sector while maintaining the competitive characteristics of the old informal businesses, including manual dismantling and private e-waste collection networks. Those characteristics ensured increased reuse value and sufficient e-waste sources. Meanwhile, the study found that many challenges and conflicts during this transition are rooted in the often-overlooked societal and historical contexts that profoundly shaped the local recycling industry. Authorities of regions facing challenges regulating informal recycling of e-waste, especially developing countries, could initiate similar systems based on local realities and the collaboration between formal and informal sectors to minimize the environmental and societal consequences of unregulated informal e-waste recycling.

Keywords: e-waste management; informal recycling; formal recycling; contextualization; waste electrical and electronic equipment (WEEE)

Abbreviations: PBDEs: polybrominated diphenyl ethers; GCEIP: Guiyu Circular Economic Industrial Park; WEEE: waste electrical and electronic equipment; CECEP: Energy Conservation and Environmental Protection Group; PCBs: printed circuit boards; ICs: integrated circuits; Bo2W: best-of-two-world

1. Introduction

1.1. Relations between formal and informal recycling

The end-of-life treatment of waste includes formal recycling and informal recycling. Formal recycling refers to government-authorized recycling enterprises with standardized processing procedures and appropriate waste management [1]. In contrast, informal recycling refers to small-scale recycling enterprises employing low-technology and low-cost operations that often pose a significant risk to the environment and human health [2]. Globally, researchers have explored the possibility of and evaluated the outcomes in regard to integrating formal and informal sectors. In a case study of municipal solid waste collection in Mexico, Guibrunet [3] illustrated that informal recycling could increase the system's sustainability if integrated into formal collection service. In another case study in Brazil, the cooperation between the formal system and informal waste pickers led to a noticeable increase in the overall recycling system's productivity [4]. Similarly, in Accra, a city with 20-year experience with informal solid waste management in Ghana, collection coverage and recycling rates have significantly increased after two years of collaboration between informal providers and formal providers [5]. However, with successful practices documented for general waste management, empirical studies are limited regarding e-waste recycling.

1.2. Global context of the case

With the soaring manufacturing and use of electronics, e-waste has become a global concern. In 2019, the world generated over 50 million tons of e-waste, i.e., 7.3 kg per capita [6], approximately 80% of which was processed in informal sectors [7–9]. Guiyu town, known as one of the largest informal e-waste recycling sites in the world, is located in the eastern Guangdong Province of China. E-waste generated worldwide was transported to Guiyu and informally recycled, which became the dominant local business that peaked during the 1990s. Researchers studied extensively the environmental contamination and human health damages associated with informal recycling in Guiyu, including the pollution of heavy metals and polybrominated diphenyl ethers (PBDEs) in the air, soil and water [10–16], elevated blood lead levels of children [17,18], a decrease in children's physical growth [19,20] and damage to lung functions [21].

Driven by the pressing need for environmental protection and remediation, the state government, local government and Guiyu residents seek to transform the informal sectors, striking a balance between economic development and environmental protection. One effort is the development of the Guiyu Circular Economic Industrial Park (GCEIP), a national-level circular economy initiative [22]. "Circular economy" refers to innovations under the constraints of sustainability, functioning with the principles of reduce, reuse and recycle [23]. Specifically, Guiyu's goal is to transform the previous informal recycling business into a formal management system within a centralized site (GCEIP) that offers high-tech facilities and supportive eco-infrastructure for e-waste recycling.

1.3. Research questions

GCEIP finished construction in 2017 and has so far successfully operated for five years. Similar industrial parks were built in other regions in China, including Beijing, Tianjin, Qingdao and Hangzhou [2,24], but all faced profitability challenges due to insufficient e-waste feedstock. Therefore, how GCEIP managed its e-waste sources can provide practical experience to those similar initiatives, including but not limited to utilizing original local networks, increasing official acquisition channels, classifying the types of e-waste and recycling accordingly, etc. The analysis is detailed in the discussion.

Additionally, e-wastes were routed to other developing countries due to China's stricter regulations on illegal transboundary e-waste. Therefore, GCEIP's political design, technological advances and financial solutions can offer unique insights for those regions regarding transforming informal recycling to formal recycling.

To achieve the above-mentioned goals, five research questions arise:

1. How successful is the GCEIP program in establishing a formal sector that integrates the informal sectors?
2. How have the formal and informal sectors been tailored and under what framework?
3. What roles have the three pillars of sustainability (societal, economic and environmental) played in this systematic effort?
4. What advantages or disadvantages does Guiyu's program have compared with similar initiatives?
5. What are the limitations and trade-offs of the program, and to what extent can it be a frame of reference for other countries and regions, particularly in the developing world?

To answer those questions, an empirical case study was developed based on multiple sources of data, including publicly available government reports, on-site observations in GCEIP and in-depth interviews with experts in the local e-waste recycling business. In this study, we first summarize Guiyu's transition from informal to formal recycling, made possible by the design and implementation of GCEIP. Building on this empirical case, the discussion centers on integration of informal into formal sectors in e-waste management, including the advantages and disadvantages, the barriers and the changes required in the recycling business landscape. We then analyzed the synergy of the solution and compared it with similar efforts on national and global levels to detail the success factors of GCEIP. We argue that the success factor in e-waste management lies not in excluding the entire informal recycling industry but in collaboration between informal and formal sectors. Lastly, we summarized the key operations facilitating the collaboration, the trade-offs made within the program and the potential applications in other regions, especially in developing countries. This research affirmed the importance of a localized response, with existing organizations and business relationships, to achieve a more sustainable recycling industry. The analysis presented here shows how researchers and policymakers can identify the unique advantages of informal activities grounded in local socio-economic realities for specific regions and can, thus, integrate those advantages more effectively into formal sectors.

2. Materials and methods

This study used (1) qualitative data collected from publicly available reports from authorities and publications and (2) quantitative data collected from empirical field research, including observations in the GCEIP and in-depth interviews with managers and experts from the formal sectors (including those transformed from informal sectors), local authorities and research institutes. The detailed information of the collected data is listed in Table 1.

Table 1. Empirical data sources and collection methods.

Group	Stakeholders	Collection methods
Formal sectors	TCL Deqing Environmental Protection and Development Co., Ltd. (Appliance recycling factory); Energy Conservation and Environmental Protection Group (Pyrometallurgy factory); GCEIP (Administration Office)	Observations and interviews
Formal sectors transformed from informal sectors	Private informal recycling businesses, including • Phone dismantling line • Hard drive dismantling line	Observations and interviews
Local authorities	Shantou Chaoyang People's Government	Interviews
Research institute	Guangdong University of Technology (Hydrometallurgy factory)	Interviews

3. The case of integration of informal sectors into formal sectors in Guiyu

This section examines the initiation, construction and implementation stages of GCEIP to evaluate its sustainability through societal, economic, political and technical perspectives.

3.1. Barriers

Prior to GCEIP, the Guiyu government made multiple efforts to regulate the uncontrolled recycling business and unfortunately failed. For instance, Guiyu authorities tried to eradicate the informal business many times after the ban of illegal e-waste imports (Basel Convention) was ratified by China in 2000, but informal sectors repeatedly rebounded. Because informal recycling requires minimal skilled labor and equipment, those backyard workshops could easily move the business somewhere else: if not in towns, then in rural villages; if not during daytime, then at midnight. The government simply did not have enough budget to enforce regulations when facing thousands of adaptive, mobile and scattered backyard workshops. For example, as of 2007, the entire recycling industry's output value reached 1.56 billion Chinese yuan, whereas the tax revenue was only 16 million Chinese yuan [25]. The shortage of the tax reflected another hidden drawback of informal recycling: With most unlicensed and unregistered backyard workshops, local governments cannot collect enough money via taxes to initiate environmental protection projects. Meanwhile, eliminating informal recycling meant cutting off the income of most families because the value of e-waste recycling accounted for more than 90% of the town's total industrial output. State and local governments must seek alternative solutions.

In 2005, Guiyu was selected as one of the regions to construct a national-level pilot circular economy industrial park (i.e., GCEIP) to improve the sustainability of the local recycling industry [26]. (A list of milestones leading to the construction of GCEIP can be found in Table S1 in the supplementary materials.) However, GCEIP was not constructed until 2012 due to the economic and societal conflicts between the pre-existing informal sectors and the newly developed formal sectors.

Concerning economic conflicts, backyard recycling workshops resisted the transformation to formal recycling due to the increased investments for equipment and costs for legal e-waste feedstock. Resistance also originated from the social realities: Most locals doubted their ability to start any other type of business after having been participating in e-waste recycling for nearly forty years. Some residents believed that informal recycling had already ruined the environment, and the local government would ruin the economy by transforming those backyard workshops into formal businesses, a double loss. Therefore, it is critical to design policies that sufficiently address these barriers and resistance before operating GCEIP.

3.2. Policy design

Previous studies examined the importance of a practical legal framework for financial support in reshaping the recycling industry [2] and promoting the circular economy [27]. Additionally, from the perspective of public management, the government bears the primary responsibility to regulate e-waste management because recycling and processing of e-waste influence the social and economic relations of society [28]. In 2000, although the Chinese government ratified the Basel Convention that advocated for prohibiting illegal export of hazardous waste from developed countries to developing countries [29], illegal e-waste was continuously transferred to Guiyu from Shenzhen port or farther ports such as Dalian and Guangxi. To stop illegal imports, China further executed regulations with detailed restrictions on electrical and electronic equipment (WEEE) imports, i.e., "Technical Policies for Controlling Pollution of WEEE" (effective in 2006) and "Measurement for the Administration of Prevention and Treatment of Pollution by Electronic Information Products" (effective in 2007). However, as of 2009, 70% of e-waste received by China remained illegal [30]. Therefore, the foremost task for the Chinese government was to establish a series of more comprehensive and effective policies regulating the import of transboundary e-waste and the construction of recycling facilities aimed at a circular economy. WEEE management policies before 2011 were explained in numerous studies [22,31]; Table 2 summarizes the political efforts after 2011, many of which greatly influenced the informal recycling industry in Guiyu. For example, the China WEEE issued in 2011 has a special provision for backyard workshops in the informal recycling sectors, as it prohibits organizations or individuals without qualifications for WEEE disposal from entering the recycling industry. Another example is the funding system (i.e., subsidies) for recycling and processing WEEE established in the *Measures for the Collection, Use, and Management of Funds for the Disposal of WEEE*. This fund system provides the companies in the formal recycling industry with subsidies to compensate for the costs of equipment and management. Large companies in formal recycling sectors, such as the TCL Deqing Environmental Protection and Development Co., Ltd., were incorporated into GCEIP under this funding system.

Table 2. An overview of e-waste and circular economy-related policies in China after 2009 (Compiled from China National Laws and Regulations Database).

Time	Legislation and regulations	Key components
2011 effective; 2019 revised	Regulation on the administration of the recovery and disposal of waste electrical and electronic products (China WEEE)	With the approval of the provincial government, a centralized disposal field for waste electrical and electronic products can be set up.
2012 May	Measures for the collection, use, and management of funds for the disposal of waste electrical and electronic products	The producers of electrical and electronic products and the consignee or agent of imported electrical and electronic products are taxed. The taxes collected are passed on to recycling plants as a fixed subsidy based on the number of dismantled appliances.
2013 May	Administrative measures for the circulation of the used electrical and electronic products	Introduce "used electrical and electronic products". Strengthen the circulation of used electrical and electronic products; promote the comprehensive utilization of resources; registration is required with detailed information such as original vouchers and sellers for used electrical and electronic products.
2015 February	Disposal catalogue of waste electrical and electronic products (2014 Edition)	The range of products covered was extended to 14 products, namely: refrigerators, air conditioners, washing machines, electric water heaters, gas water heaters, printers, copiers, fax machines, televisions, monitors, computers, mobile communication handsets, telephones (Amended in 2016 March).
2016 July	Measures for the administration of the restricted use of the hazardous substances contained in electrical and electronic products	Introduction of "electrical and electronic products" and "pollution caused by electrical and electronic products"; restrictions on the use of the hazardous substances contained in electrical and electronic products. Development of "catalogue for the standard compliance administration of the restricted use of the hazardous substances contained in electrical and electronic products".
2017 January	Implementation plan for the extended producer responsibility (China EPR)	Introduction of the main body, objects and mode of implementation for the EPR; promote eco-friendly design and encourage the use of renewable resources; set up recycling standards.
2017 July	Implementation plan for prohibiting the entry of foreign garbage and advancing the reform of the solid waste import administration system	A total ban on the entry of "foreign waste". Starting from January 2018, China stopped importing twenty-four types of foreign garbage. By the end of 2019, the import of solid waste that domestic resources can replace will be phased out.
2018 April	Import waste management catalogue	Sixteen types of solid waste such as scrap metal, waste ships, scrap car parts were removed from "the catalogue of solid waste restricting imports used as raw materials" and transferred to "the catalogue of prohibited imports of solid waste" (implemented since December 31, 2018).
2008 effective; 2018 amended	Circular Economy Promotion Law of the People's Republic of China (2018 amendment)	For products such as electrical and electronic equipment that may cause environmental pollution during dismantling and disposal, the use of toxic and hazardous substances is prohibited during manufacturing; improving the resource utilization efficiency concerning reducing, reusing and recycling activities in production, circulation and consumption; encouraging and supporting the research and education of science and technology related to a circular economy.

3.3. Implementation

The construction of GCEIP has advanced throughout the years with support from national, provincial and municipal governments. This section introduces the major facilities, the companies in residence, the source control methods and the recycling technologies implemented by GCEIP.

Table 3. The functions and capacities of major plants and projects constructed in GCEIP after 2014 (Complied from local newspaper, websites, and interviews).

Project	Year	Functions	Capacity
TCL appliances dismantling factories	2014	Recycling computers and appliances; only complete televisions, refrigerators, washing machines and air conditioners are accepted; invested by TCL Deqing Environmental Protection and Development Co., Ltd.	50000 tons/year
Physical separation facilities	2014	Recycling of waste printed circuit boards (PCBs) via physical separation with hydraulic shakers. Burning and acid leaching are excluded.	60000 tons/year
Sewage treatment plant	2015	Household wastewater treatment in Guiyu town	30000 tons/year
Disassembly facilities	2016	Phase I: the manual dismantling of waste PCBs Phase II & III: manual dismantling with tools such as pliers and hammers; manual sorting of plastics, cables, wires, aluminum, etc.	
Pyrometallurgy facilities	2016	Pyrometallurgical treatment of waste PCBs (bare boards), invested and managed by Shantou Recycling Resources Technology Co., Ltd, an enterprise of the state-owned company China Energy Conservation and Environmental Protection Group (CECEP). By 2017, its annual capacity increased to 20000 tons from 10000 tons.	20000 tons/year
Hydrometallurgy facilities	2016	Hydrometallurgical treatment of integrated circuits (ICs) to recover precious metals. The patent belongs to the University of Guangdong Technology. Waste acids solutions were processed via the Mechanical vapor recompression (MVR) technique with inorganic salts as end products.	5000 tons/pear
Waste transfer stations	2017	Two out-park transfer stations at Xianma and Guiyu counties with twenty-six waste collection locations.	N/A
Hazardous waste transfer stations	2017	In-park hazardous waste transfer	160000 tons/year
Waste plastic cleaning plants		Seven plants for cleaning waste plastics before sorting, located among the disassembly buildings	N/A
Industrial wastewater treatment plant		GCEIP wastewater treatment	6000 tons/day
Guiyu electronics trade market		The upgraded platform consolidated markets among Guiyu and neighboring regions for transactions of waste electronic components and metals.	N/A
Loading lot		Loading and unloading of e-waste, functional components and recycled products. The sources, categories and weight of incoming e-waste need to be registered before acceptance. Imported e-waste is prohibited.	N/A

Table 3 lists the details of major projects completed during GCEIP's construction. The programs or plants all bear the purpose of advancing and centralizing waste management in the e-waste recycling industry.

3.3.1. Companies in residence

GCEIP's strategy to integrate informal sectors into formal sectors contained three steps, downsizing informal sectors, developing formal sectors, certifying and transforming previous informal sectors to formal business by offering standard recycling and waste treatment equipment. To put the strategy into context, previous backyard workshops were reorganized into 49 private companies focusing on recycling PCBs or plastics, all of which have operated in GCEIP from 2016 onward with a two-year tax exemption period. Details of the reconstruction of those 49 companies are explained in Section 4.2.1. With subsidies, the Guiyu government also invited enterprises in the formal recycling sector to reside in GCEIP to increase the recycling capacity to achieve economies of scale and to boost profitability. For example, TCL Corporation (a leading multinational electronics enterprise) and a local company in Guiyu co-founded TCL Deqing Environmental Protection and Development Co., Ltd. The joint venture invested 50 million Chinese yuan in building appliance dismantling factories (24000 m^2). The company was certified at the end of 2014, operating and receiving state subsidies with an annual capacity of 50000 tons, equivalent to 1.2 million sets of electrical appliances. (The recycling procedures of waste electrical appliances were detailed in the supplementary materials as Figure S1). Those large companies brought jobs for people previously working in the informal sectors and stimulated local economic growth.

3.3.2. Source control of e-waste

To ensure the incoming e-waste feedstocks were obtained from licensed sources, GCEIP issued site access cards to each company in residence. Trucks carrying e-waste entering the parking lot must present access cards. Incoming e-wastes were then registered with sources and weights. GCEIP executed three routes for trading e-waste feedstocks. First, when upstream collectors send e-wastes directly to GCEIP, the private companies can bid, and the company with the highest bid would claim the ownership. Alternatively, individual private recycling companies can purchase domestic e-waste from the sellers inside their previous networks. Those e-wastes would be assigned directly to affiliated companies after undergoing registration. It is a win-win condition that, for GCEIP, guarantees a stable e-waste source with personal connections and, for private companies, offers additional profits. Lastly, TCL Deqing Environmental Protection and Development Co., Ltd., relied on appliances collected via its own network, mostly managed through the nationwide trade-in program. This trading framework eliminated competition for the feedstocks between the private companies and high-tech recycling companies but ensured the government's inspection of in-park transactions.

3.4. Recycling technologies and waste treatment

This section introduces the overall recycling operations in GCEIP, as shown in Figure 1. After passing the inspection and trading stages in GCEIP, e-waste feedstock was dismantled and categorized as (1) functional units (such as cables, bare wires or large-size electric units), (2) waste plastics, (3) waste PCBs and (4) other types of wastes. Functional units would enter the used-products trading markets; waste plastics were used to produce recycled plastic particles (cleaning, sorting and cutting); waste PCBs would undergo a refined manual dismantling process before arriving in recycling facilities, as seen in Figure 2. After this refined manual dismantling, sorted components were recycled through three standardized routes: (1) hydrometallurgy to recover gold from ICs (replacing open-air aqua regia acid baths), (2) pyrometallurgy to recover Cu from bare PCBs (replacing open-air burning of PCBs) and (3) physical separation with hydraulic shakers as a supplementary method to recover fine metal powders. These treatments replaced the rudimentary recycling technologies used in informal recycling prior to the construction of GCEIP. Technical details of the pre-processing and treatments are explained in the following section.

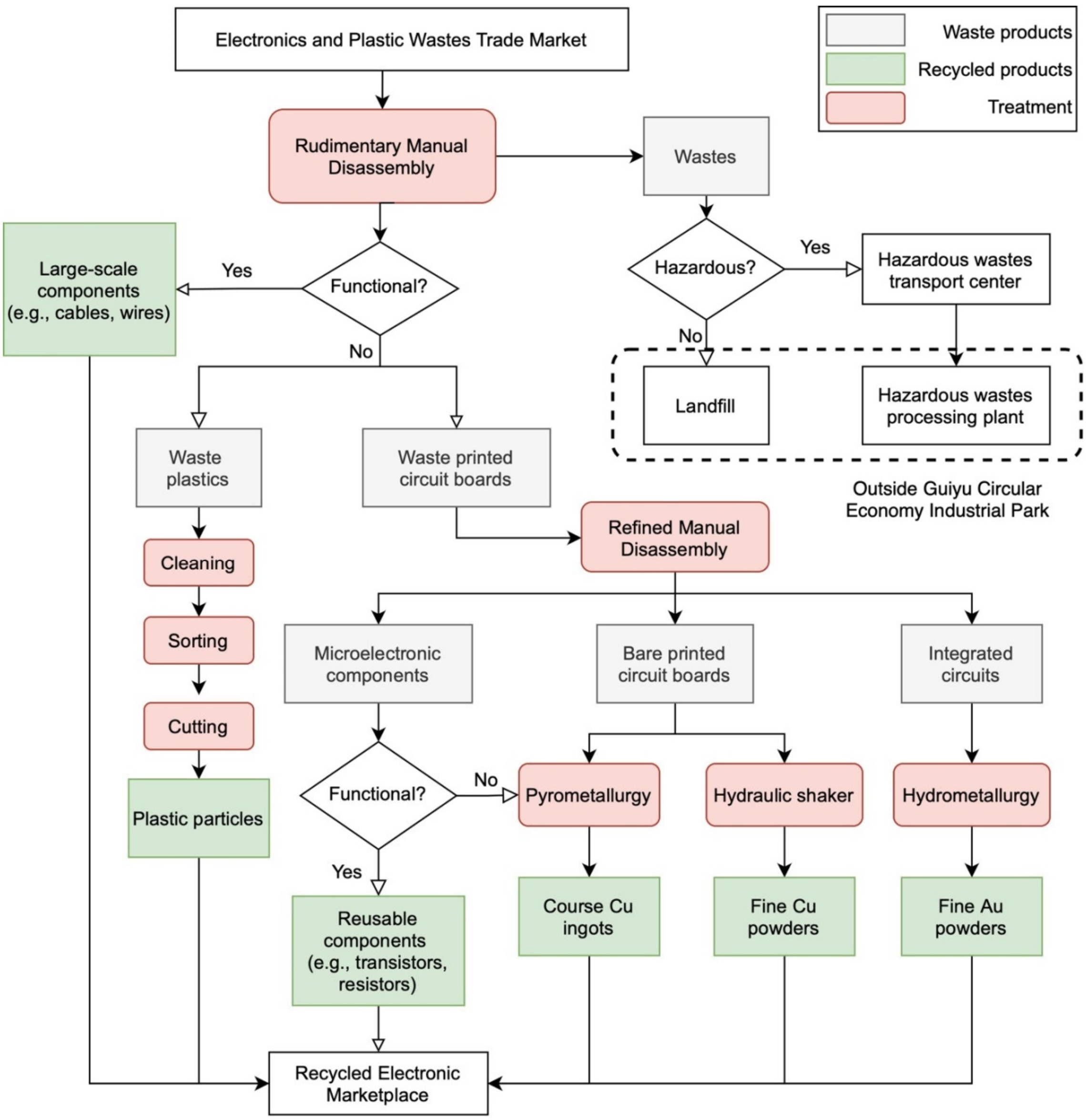

Figure 1. An overview of the mixed technologies employed in pre-processing and treatments in Guiyu Circular Economy Industrial Park.

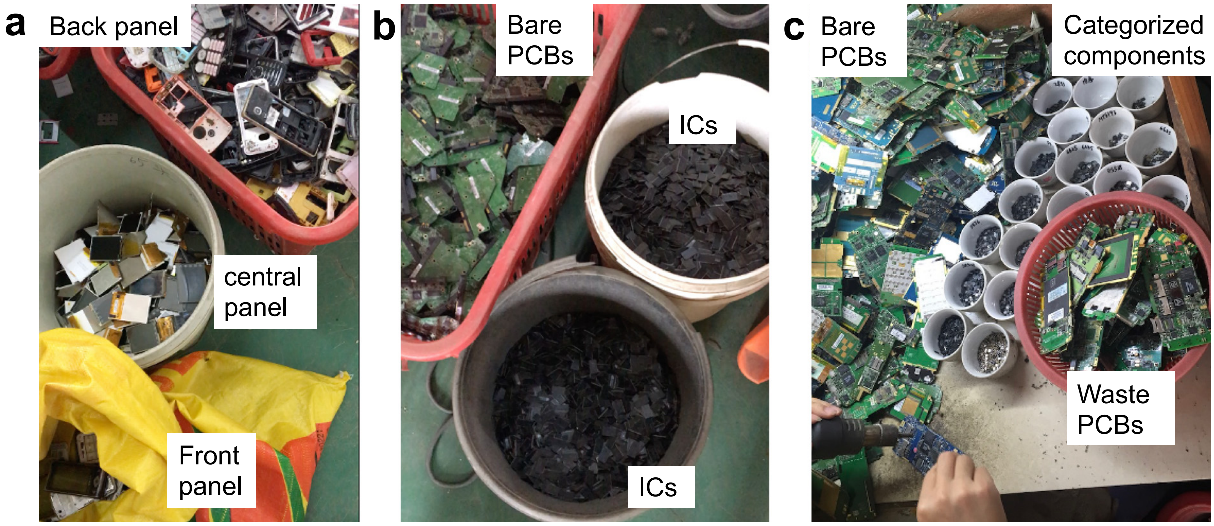

Figure 2. The end products of a cellphone dismantling procedure carried out in GCEIP. (a) dismantling the housing and large-size electronic components; (b) dismantling integrated circuits and PCBs; (c) dismantling and sorting different types of small electronic components such as cameras and memory chips. Photo credits: Congying Wang.

3.4.1. Refined manual dismantling

Manual dismantling yields a higher percentage of reusable and recyclable materials than shredding. However, in the informal sector, the manual dismantling of e-wastes often uses primitive and hazardous processes and causes harm [32]. Inside GCEIP, waste PCB private companies (those transformed from informal backyard workshops) explored "low-cost" innovations in the dismantling process, as illustrated in Figure 2. For example, instead of relying on "high-tech" dismantling factories, dismantling in GCEIP used hot air guns to partially soften the solder to remove electronic components from the boards. After sorting, dismantled microelectronic components were first tested before recycling treatments: If tested functional, units would be traded in second-hand markets; if not functional, units would be dispatched to the pyrometallurgy plant. Therefore, a large fraction of functioning components can be resold for direct reuse [33]. These innovations increased reuse and recycling ratios and improved working conditions. Such a "refined" manual dismantling process gained popularity in Guiyu many years ago, and the value of reuse and refurbishment reached 80% of the total revenue of the recycling industry [34]. GCEIP embraced this recycling and reuse model by allowing private companies to continue the refined manual dismantling operations. The high degree of separation of components still constitutes an essential characteristic of Guiyu's recycling industry, representing a salient characteristic of successful recycling businesses in developing countries [35].

3.4.2. Hydrometallurgy: Gold recovery

The hydrometallurgy plant in GCEIP received batches of sorted ICs after manual dismantling. Hydrometallurgy separates metals, primarily gold, by dissolving the ICs in different inorganic or organic solvents, followed by electrolysis or precipitation to produce relatively pure metal products. The environmental concern of hydrometallurgy is the large amount of waste acid, acid mist and waste residues generated in the process [36]. GCEIP collaborated with the Guangdong University of Technology, who designed a patented hydrometallurgy process to extract gold from ICs [37] with integrated modules to collect and filter the acid mists and waste acid via mechanical vapor compression (MVP), as shown in Figure 3. The upgraded hydrometallurgy facilities contain five processing lines for gold recovery (annual capacity of 5000 tons) and a storage facility for acids, as seen in Figure 3d.

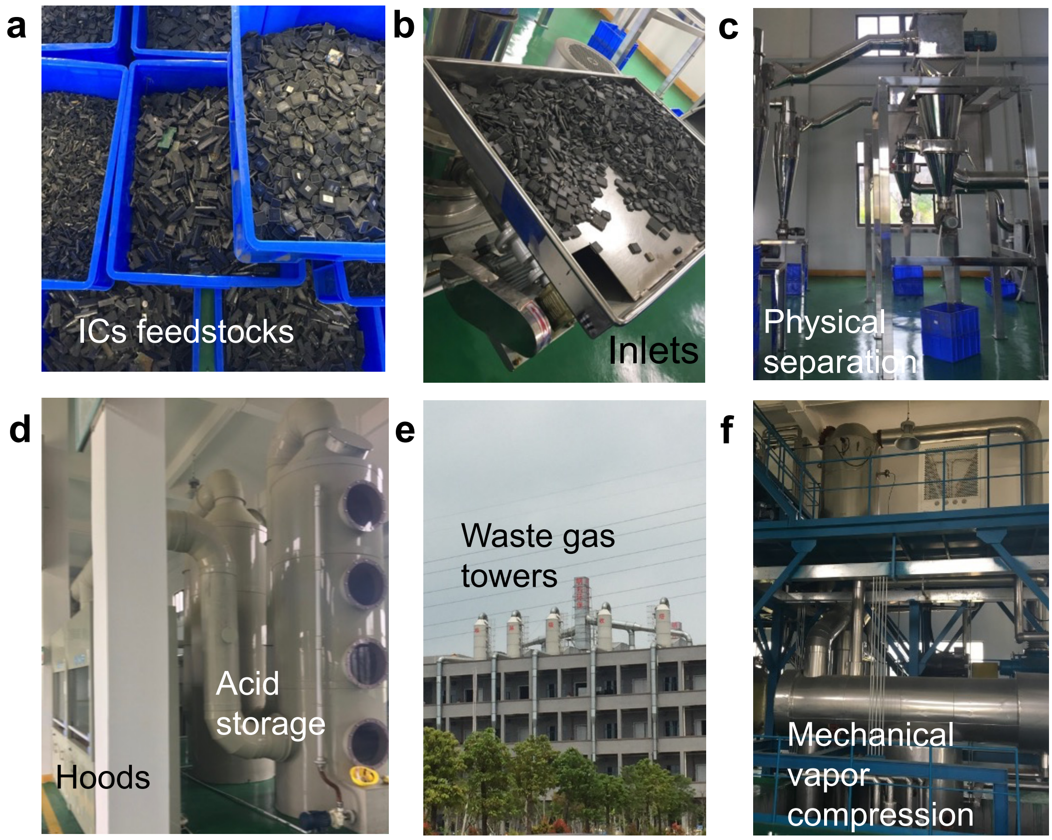

Figure 3. Recycling and treatment processes for gold recovery. (a) The stocks of dismantled and sorted integrated circuits (ICs). (b) The inlet of ICs. (c) Physical separation equipment. (d) Hydrometallurgy facilities and (e) waste gas tower on the roof of one of the plants. (f) Waste solution processing by mechanical vapor compression (MVP) equipment. Photo credits: Congying Wang.

3.4.3 Pyrometallurgy: Cu recovery

Sorted bare PCBs were transported to the pyrometallurgy plant for Cu recovery. Pyrometallurgy recovers non-ferrous metals (mainly Cu) by carbonizing non-metallic materials at high temperatures, with advantages such as low operating costs, large processing capacities and high recovery rates. Yet, two challenges existed, i.e., the substantial expense incurred by the equipment and the complex treatment of exhaust gas to remove dioxins and polybrominated diphenyl ethers [38]. Because the local government cannot provide GCEIP with either the funding or technology for pollution control, GCEIP collaborated with Energy Conservation and Environmental Protection Group (CECEP), a state-owned high-tech enterprise, to co-fund CECEP Shantou Recycling Resources Technology Co., Ltd., to invest in pyrometallurgy plants. The company developed a new pyrometallurgy technique with a controlled temperature between 1200 and 1250 ℃ so that the generation of various dioxin precursors is suppressed [39]. The pyrometallurgy plants in GCEIP were the first in China that employ bath smelting to recover copper from waste PCBs and have operated since 2016 with an annual capacity of 10000 tons. In March 2017, the capacity was expanded to 20000 tons per year.

4. Discussion

The discussion is arranged as follows: We first evaluate the outcomes of GCEIP and how GCEIP shaped the landscape of the local recycling business to answer the first two research questions listed in Section 1.3. Second, we give examples of how societal and economic aspects were considered in the synergy of the solution to answer the third question, since the technologies were extensively analyzed in Section 3.4. We then compare GCEIP with similar practices at global and national levels to analyze its advantages and disadvantages, responding to the fourth question in Section 1.3. Finally, we summarize the limitations and implications of this case study to answer the last research question.

4.1. Changes in the local recycling industry

Figure 4 illustrates the recycling industry's overall architecture in Guiyu after the construction of GCEIP. GCEIP maintained, to a large extent, the original structure of the local informal recycling sectors. Therefore, Guiyu kept the unique advantages of its local recycling industry, developed throughout several decades, i.e., broad collection networks, vast end markets, reuse value and the ability to recover distinct materials from e-waste, including plastics and various metals. In addition, GCEIP avoided severe unemployment from the banned informal sectors by integrating Guiyu's existing recycling industry. GCEIP brought the local society (1) external resources such as technologies and investments, (2) strict source monitoring of the incoming e-waste and (3) pollution management. With initial financial support from state and provincial governments, GCEIP has grown to hold 80 enterprises and about 3500 employees, with annual output values of 1.035, 1.75 and 1.465 billion Chinese yuan in 2016, 2017, and 2018 [40]. The local government's tax income has increased to 30 million Chinese yuan per year [41]. The government's increased income lowered the economic barriers to initiate future programs to restore the environment and fund advanced recycling technologies.

When evaluating GCEIP, it is necessary to consider whether GCEIP's capacity is significant at the local and national scales. Prior to GCEIP, the recycling industry in Guiyu digested 1.5 million tons of e-waste per year, the majority of which was imported; at present, GCEIP's annual capacity has reached approximately 1.08 million tons of domestic e-waste [40], more than 70% of the capacity of previous informal sectors. At the national level, however, limited and inconsistent data posed challenges to the analysis. For instance, domestically generated e-waste in China was estimated to be 4.6–9.2 million tons [42] or 15 million tons [43,44] as of 2020. Based on the maximum estimated number, GCEIP's current capacity accounts for at least 7% of the total amount of domestic WEEE. However, this is still an underestimated ratio because only a relatively small portion of generated WEEE was collected for recycling. Though we are not able to find the accurate number for China, it was estimated that merely 20% of WEEE was collected and recycled globally [8,9]. Therefore, the actual contribution of GCEIP to the nation's entire recycling industry can only be higher. We call for systematic studies about this gray area, i.e., the total amount of e-waste generated versus the percentage collected, which will greatly advance the understanding of e-waste recycling for the research community.

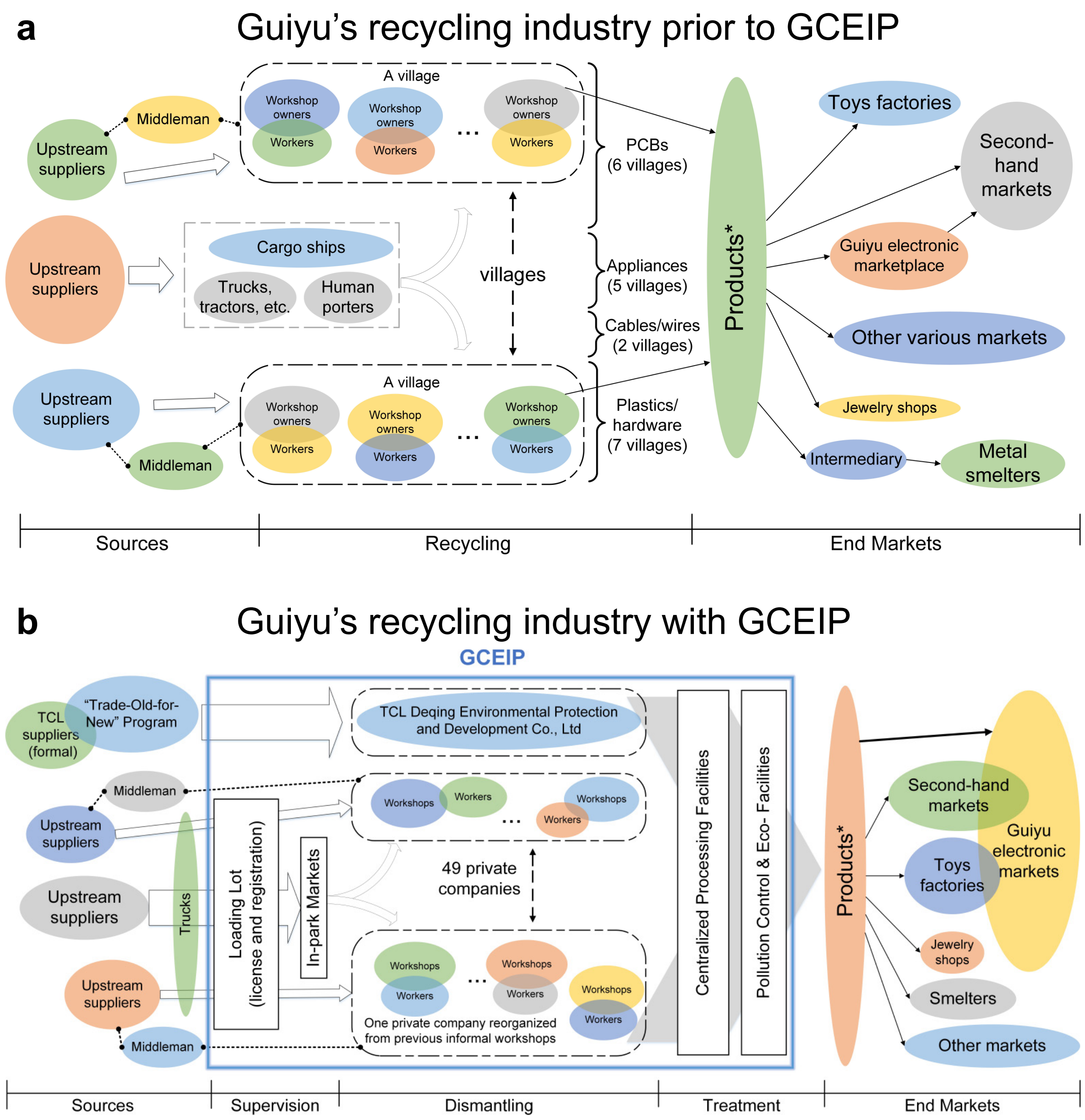

Figure 4. The recycling scheme of (a) informal sectors in Guiyu before the construction of GCEIP and (b) integrated informal sectors and formal sectors in Guiyu after GCEIP.

4.2. Synergy of the solution

Positioning GCEIP into the overall framework, Figure 5 summarizes Guiyu's solution to transform and regulate previously uncontrolled e-waste recycling activities. Four themes emerge from Guiyu's solution to transform and regulate previously uncontrolled e-waste recycling activities. The themes include (1) the construction of facilities dedicated to recycling and waste treatment in GCEIP, (2) the collaboration between GCEIP and large companies or research institutions, (3) the reconstruction of backyard workshops and (4) the establishment of the end markets. The first two themes have been discussed in previous sections, and the details of the last two themes are summarized in the rest of the section, reflecting how societal and economic factors played roles in formulating the solution.

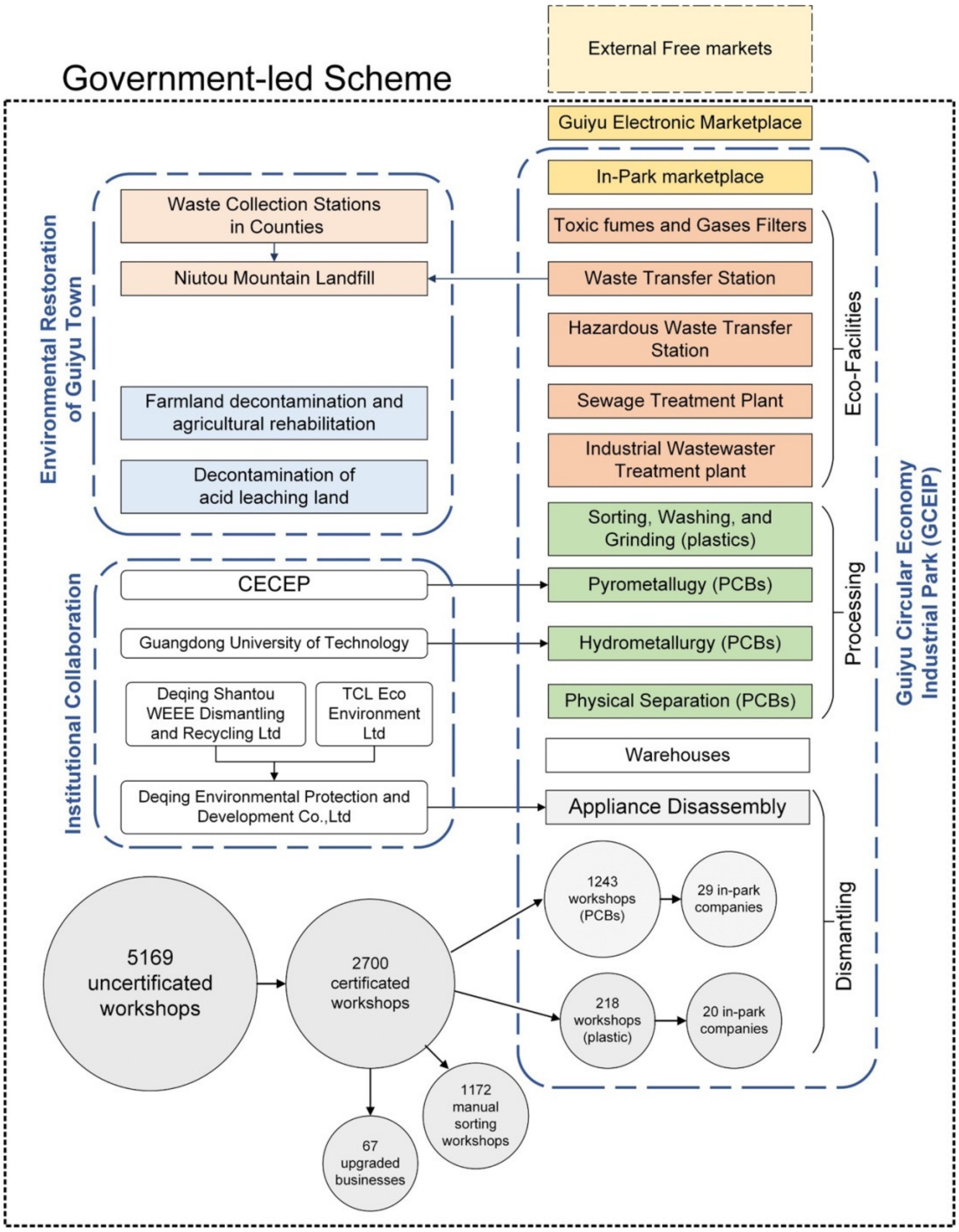

Figure 5. The overall scheme of GCEIP to manage e-waste recycling.

4.2.1. Reconstruction of backyard workshops

When the GCEIP development plan was initiated in 2012, more than 21 townships (out of 27 total at Guiyu), 300 private enterprises, 60000 people and 5000 unlicensed backyard workshops were in the informal recycling business, which digested 1550000 tons of WEEE and waste plastics per year. It was impossible to construct an industrial park capable of absorbing the entire informal sector. Therefore, the local government established a standard of environmental impact assessment and allowed one year for all workshops to meet the criteria in which uncontrolled acid leaching and open-air burning were strictly prohibited. Additionally, each workshop was required to (1) solidify the ground with concrete to prevent soil pollution from wastewater, (2) install a gas collecting hood to filter exhaust gas and (3) provide workers with protective masks and gloves. In 2013, about 3000 workshops were temporarily certified. The rest of the 2000 workshops were forced to shut down. A year later, 441 workshops that failed to pass the annual assessment were again required to close, as well as 286 unlicensed workshops that restarted operation illegally. By the time GCEIP finished the first-stage construction, about 2700 small-scale workshops had remained and reorganized as larger private companies to receive access permissions from GCEIP. In the end, 1243 workshops of PCB recycling formed 29 companies, and 218 workshops of plastic recycling formed 20 companies, all of which have operated in GCEIP since 2016. (1172 workshops that only focus on sorting plastics stayed outside GCEIP). After a year of operation in GCEIP, those 49 companies were reorganized to 80 companies based on performances.

During the reconstruction, both national-level regulations and local-level administration played critical roles. For the former, policy development such as the *Regulation on the Administration of the Recovery and Disposal of WEEE* (China WEEE in 2011) provided legal bases for Guiyu authorities to close informal recycling workshops that failed to obtain the necessary qualification. For the latter, the local government chose to step out of the reorganization process because of the strong local culture that people tend to do business with their acquaintances. Those workshops had autonomy in making decisions such as what company they attempted to set up, how many workshops should be included and who should take the management responsibility. Three primary forms of reorganization occurred, i.e., the combination of recycling workshops by geological location such as villages, by social relations such as relatives and friends or by recycling products such as gold or copper.

4.2.2. End markets of recycled products

Historically, a variety of end markets flourished in Guiyu, driven by other industries’ demand for secondary materials. In addition, the second-hand markets for electronic components boomed because of the “fine dismantling” process rooted in the local recycling industry's culture, i.e., e-waste is manually dismantled and classified to the level of transistors and resistors, as shown in Figure 2e. Components with reuse values are sorted, tested, and sold on the local market. For example, toy factories in neighboring towns often purchase second-hand but functional motors to produce toy cars. However, the reuse practice mentioned above lacks proper inspection, which may cause (1) hardware quality problems regarding product functions and product life, (2) patent risks due to the authorization of components and supporting software and (3) information security problems concerning the reuse of storage components [43]. In view of the above concerns about hardware, software and information security, this industry still needs to be regulated and managed.

Concerning trading, a common question is "who owns the recycled products?" especially for valuable metals such as gold. Indeed, though the local government established an electronic trading market to provide a licensed platform for trading recycled products, the end markets still heavily rely on the "old" social connections or supply chains built by previously informal family workshops. Private businesses in GCEIP can determine which end markets they want to enter or which agents they want to use for marketing recycled products, after paying the fee of operating recycling facilities. If those businesses fail to find appropriate buyers, GCEIP can purchase, collect, sell, and distribute those recycled or recovered products.

4.3. Comparisons between GCEIP and similar efforts

GCEIP is one representative case study of transforming informal recycling to formal recycling, but it is not the only one. This section compares GCEIP with similar projects both inside and outside China to explore whether the Guiyu case study can be a model for sustainable recycling internationally and what the limitations of the model are.

4.3.1. National level

On the national level, the Chinese government has initiated similar programs to shape e-waste recycling under the framework of the circular economy. Generally speaking, those programs can be classified into two categories: One adapts state-of-the-art recycling facilities and technologies such as the recycling plants in Qingdao; the other absorbs the existing industry and relies on technologies that are tailored for local realities. GCEIP belongs to the latter. One may argue that Guiyu could construct brand-new formal recycling plants, considering many other high-tech industrial facilities have been built recently in China [31]. However, the lack of e-waste sources has emerged as the main challenge confronted by those recycling plants. For example, one of the formal recycling factories in Tianjin, China, has faced a shortage of incoming e-waste since finishing construction [1,45–47]. Similarly, Hangzhou Dadi recycling industrial park only reached 4% of its maximum capacity (284 out of 7000 tons) as of 2006 [47]. This issue is deeply rooted in the lack of a formal WEEE collection system in China. Traditionally, except for the second-hand markets, the rest of the WEEE was collected by individual peddlers [2]. Therefore, without a systematic collection network under the local government's supervision, the volume of feedstock collected by formal sectors is insufficient for the recycling industry to reach a profitable scale. In comparison, GCEIP overcame the shortage issues by taking advantage of the collection network established by previous backyard workshops, as detailed in Section 3.3.2. GCEIP's framework affirmed the importance of the collaboration between local community and authorities in designing e-waste management policies, as previously indicated in Palestine's cases [48].

4.3.2. Global level

Though regional governments can ban all informal recycling to mitigate the damage, the proper treatment of e-waste remains a challenge on the global scale due to the mobility of WEEE, i.e., banning may not be the most desirable solution. For instance, with China's stricter regulations on transboundary e-waste, alternative e-waste dumping sites in other developing countries emerged, such as Thailand and Malaysia [49]. To prevent the damage of e-waste recycling from remaining solely a third-world problem, researchers also seek solutions to bridge and combine the value of manual dismantling (usually in developing countries) and that of waste management (usually in developed countries), such as the best-of-two-worlds model [50]. The best-of-two-worlds (Bo2W) model proposed local-scale collection and dismantling enterprises (usually in developing countries) and global-scale high-tech treatment (usually in developed countries). Both GCEIP and the Bo2W advocate for using manual dismantling at the pre-processing stage and employing technically advanced facilities at the end-processing stage. Additionally, GCEIP's approach included filtering out illegal transboundary e-waste, establishing a domestic recycling network, and shortening the time to payment of informal recyclers for materials recovery from e-waste, a major barrier observed in the implementation of the Bo2W approach. Though GCEIP seems to echo the Bo2W philosophy at a local scale, scaling up this practice to a regional scale will result in additional challenges, especially ethical problems. This is because the collaboration between developed countries and developing countries may turn out to justify unfair shares of rights and responsibilities: who pays for who; who generates, uses and discard electronics; who offers treatment, and where the waste goes.

4.3.3. Limitations

The Guangdong province, Shantou city, Chaoyang district, and Guiyu town have jointly invested 1.53 billion Chinese yuan in building GCEIP. However, the maintenance of current facilities and the construction of subsequent projects still need a considerable amount of investment. The local government needs to repay the previous loan principal and interest of 400 million Chinese yuan, plus the fees for GCEIP's daily operations. GCEIP still heavily relies on the state government's budget fund; e.g., its expenditure budget for 2020 is 145 million Chinese yuan [41]. The fundraising needs are still urgent and remain the most significant barrier to long-term success.

After five years of implementing GCEIP, the number of published papers and reports regarding the changes in Guiyu is still limited. A study by Schulz and Lora-Wainwright [51] claimed that the local elite manipulated the transition under the guise of a "circular economy" because of the continuing uneven distribution of power and wealth. While this uneven distribution is a reality, it is not caused by the creation of GCEIP. It is critical to examine the situation through a historical lens, as demonstrated in this study. The socially and financially disadvantaged groups (e.g., local poor, migrant workers) and elite class existed long before GCEIP. Indeed, the effort of transforming the informal activities should and could further improve, but the environmental or societal damage resulting from four decades of unregulated informal recycling should not be attributed to GCEIP. It is vital not to underestimate the struggles that developing countries have faced when examining recycling activities from outside.

5. Conclusions

Guiyu used to be the largest informal e-waste dismantling and distributing center in the country and even in the world. Since the late 1980s, Guiyu started a profitable informal dismantling business when foreign e-waste entered Guiyu in large quantities through the transfer points of Shenzhen, Guangzhou and Hong Kong. By the 1990s, 80% of the families in Guiyu participated in the informal e-waste recycling industry. As of March 2012, there were 5169 dismantling operations in the town with more than 100000 employees. It is also one of the most recognized victims of the pollution caused by informal e-waste processing. In the past decade, the GCEIP has shifted the informal, heavily polluted recycling business to a “technology-hybrid” industry. During this transition, relevant legislation via top-to-bottom policy design, localization within societal and economic contexts and accessible technologies through collaborations are critical themes.

First, policies and legislation are of great significance in driving the informal recycling sector to abandon illegal recycling techniques and transboundary e-waste. In Guiyu’s case, the initiation and implementation of GCEIP are closely related to the progress of environmental legislation by the Chinese government. For instance, *Regulation on the Administration of the Recovery and Disposal of WEEE* prohibits the recycling or disposal of e-waste by businesses and individuals that have not obtained specific qualifications, which targeted backyard recycling workshops in Guiyu. *Measures for the Collection, Use, and Management of Funds for the Disposal of WEEE* stipulated that the state establishes a WEEE product disposal fund to subsidize the processing costs of WEEE products.

Second, although GCEIP drastically reformed local informal sectors, the recycling industry in Guiyu retained its societal and cultural structure. GCEIP could have faced enormous resistance if the recycling industry’s history and traditions had not been respected. The intrinsic driving force for a circular economy relies on the regional innovation led by the government and enterprises, such as the manual dismantling techniques with heating to prevent burning the PCBs in workshops and creating dioxins. Enterprises in the GCEIP are self-organized and market-oriented. GCEIP expands the existing e-waste source network, thereby avoiding the pitfalls resulting from a shortage of feedstock for recycling.

Third, technology and informal recycling are not mutually exclusive. GCEIP manifests a collective effort of national-owned companies, private companies, “used-to-be” informal recycling businesses, research institutes and thousands of workers. The government could provide subsidies to motivate big companies to join the recycling industry; research institutes could promote the applications of novel technologies or patents; private companies in recycling businesses could reconstruct to establish effective communication between each sector.

On a global scale, however, the question becomes complicated. If the global concern of e-waste inevitably turns into a local problem, especially in developing countries, the solution must also be local. Guiyu offers invaluable lessons in how to deal with e-waste in other regions where tailor-made solutions and multi-year efforts must be sustained. Particular advantages of informal sectors are rooted in the historical, societal and economic factors in the local context. It is critical to locate, direct and incorporate those advantages when developing a sustainable e-waste recycling industry. Formal recycling and informal recycling are not mutually exclusive, and the alignment between the two sectors can be achieved with a contextualized understanding of the local recycling industry.

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Conflict of interest

The authors declare no conflict of interest.

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