Analyzing present and future availability of critical high-tech minerals in waste cellphones: A case study of India

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Abstract: Critical high-tech minerals (CHTMs) are raw materials that are essential for a future clean-energy transition and the manufacture of high-end products. Cellphones, one of the fastest growing electronic products, contain various CHTMs. Since 2019, India has surpassed the United States to become the second largest smartphone market in the world. An increasing and alarming number of excessive waste cellphones will be generated in India in the near future. In this study, the dynamic material flow analysis approach and the Weibull distribution are adopted to analyze the volumes of accumulated waste cellphones and the contained CHTMs based on the differentiation between smartphones and feature phones in India. Moreover, a market supply model is adopted to predict the future trends of CHTMs in waste cellphones. The results show a general upward tendency of waste cellphone volume in India, which indicates that various CHTMs contained in cellphone waste can be properly reused or recycled. Future implications based on the analysis results are provided for efficient cellphone management in India.

Keywords: Material flow analysis, Critical high-tech minerals, Waste Electrical and Electronic Equipment, Printed Circuit Boards

1 Introduction

Critical high-tech minerals (CHTMs) are "minor" metals on which modern technology is cumulatively reliant to perform specialized functions (Nassar et al., 2015). The stocks of CHTMs on earth are limited, and acquiring them from natural virgin ore is difficult due to technical and economic limitations (He et al., 2018). The availability of these CHTMs is, thus, reliant on not only the specific mining production of their host mineral(s) but also whether the companion minerals are properly recovered rather than discarded without having been processed (Nassar et al., 2015). Furthermore, demands for materials and metals will increase with technological development, because the World Bank reported that "the clean energy transition will be significantly mineral intensive" (Oberle et al., 2019; World Bank, 2018). Urban mining is a potential alternative for addressing the challenges related to the continued strong demand for CHTMs and fragile supply of CHTMs. Urban mining has been efficiently utilized for resource extraction of electrical and electronic products and industrial waste (Hu et al., 2020; He et al., 2020; Cossu et al., 2015).

The rapid advancement of technological innovation has led to a substantial increase in the demand for CHTMs (Nassar et al., 2020; Randive et al., 2019). The Indian economy has been growing rapidly at an annual rate of 7.1% in the past decade, which positions India as an emerging world economy (Poonam., 2018). In the Indian economy, the electronic industry, including production, internal consumption and export, is one of the fastest-growing sectors (Dwivedy et al., 2010; Dimitrakakis et al., 2006). India recently surpassed the United States as the second-largest smartphone market behind China, when it reached 158 million shipments in 2019 (Anshik, 2020). Cellphones, one of the fastest-growing electronic products, contain various CHTMs. Two types of cellphones exist, namely, feature phones and smartphones. Specifically, the major CHTMs, such as cobalt and palladium, are contained in waste feature phones, while antimony, beryllium, praseodymium, neodymium, and platinum are also contained in waste smartphones (Cucchiella et al., 2015). Despite being a relatively rich country in terms of mineral resources, India's dependence on imported minerals is high, next only to oil (Randive et al., 2019). Therefore, waste cellphones represent a potential crucial reservoir of CHTMs for urban mining in future decades.

In the global context, previous research on waste cellphones has primarily focused on waste generation and various minerals contained in waste. Ongondo et al. (2011) estimated that approximately 3.7 million cellphones are stockpiled by university students in the UK, while approximately 28.1 million cellphones and 29.3 million cellphones are stockpiled in the USA and Europe, respectively. Polák et al. (2012) estimated that the Czech Republic produced 45 thousand waste mobile phones from 1990-2000; this number increased to 6.5 million from 2000-2010 and is estimated to increase to approximately 26.3 million phones from 2010-2020. Rahmani et al. (2014) indicated that approximately 39 million waste mobile phones accumulated in 2014 in Iran, but the portion that could possibly be reused portion was only 4.2 million. Through the end of 2035, it is projected that approximately 90 million waste mobile phones will be discarded in Iran. Li et al. (2015) utilized the sales & new method and estimated that approximately 47.92 million waste cellphones were generated in 2002 and approximately 739.98 million waste cellphones were generated in 2012 in China. Tan et al. (2017) predicted future quantities of waste metals/minerals from waste mobile phones in 2025 in China. With 100% recycling, approximately 9.01 tons of Au and 14.91 tons of Ag can potentially be extracted from printed circuit boards (PCBs). Babayemi et al. (2017) indicated that approximately 54,050 tons of mobile phones have been transported to Nigeria during 2001 and 2013; these phones contained 8920 tons of copper, 270 tons of nickel, 120 tons of lead, 40 tons of chromium and 1310 tons of bromine from brominated flame retardants. Holgersson et al. (2018) analyzed the metal/mineral content of waste smartphones and waste feature phones in Sweden and discovered that the lead content in smartphones is lower than that in feature phones, while the contents of other toxic metals/minerals are similar. He et al. (2018) conducted a study on HTMs in waste mobile phones and measured a considerable quantity of HTMs stored in waste cellphones that could be recycled in the Chinese market. Liu et al. (2019) concluded that non-PCB components of waste mobile phones account for more than 50% of the total economic value in terms of the recovery potential. Sahan et al. (2019) estimated that the economic value of nearly 1.72 million USD and 37.6 million USD could be generated from recycling basic metals and precious metals in PCBs. Li et al. (2020) utilized the minimum distance maximum receiving (MDMR) algorithm and reported that more than 400 million units of waste mobile phones could be recycled in China.

In the Indian context, Rathore et al. (2011) determined that India generated approximately 1700 tons of waste mobile phones, and the number of mobile phones discarded in 2020 will be 18 times higher than that in 2007. Sharma et al. (2013) revealed that the number of wireless connections renders India the second-largest telecommunication network in the world, following China. Vats et al. (2015) estimated that the recoverable metallic fractions of gold and silver in the PCBs of mobile phones in India is in the range of 0.009–0.017% and 0.25–0.79% by weight, respectively. Borthakur et al. (2019) conducted a survey in Bangalore, India and discovered that mobile phones in Bangalore are phased out within the product lifetime. Moreover, the number of mobile phones per person that are “in-use” is much lower than the number of “unused” mobile phones in Bangalore. Ravindra et al. (2019) indicated that approximately 4100 tons of electronic waste, which comprise 3400 tons of hazardous substances (i.e., heavy metals and plastics), is generated annually in Chandigarh, India. Moreover, the National Mineral Exploration Policy (NMEP) was announced in India in 2016 to recognize the importance of critical minerals for industry, which is a step in the right direction to achieve the security of important mineral commodities (Gupta et al., 2016; Randive et al., 2017). In summary, abundant studies regarding waste cellphone generation and the various minerals contained in such waste have appeared in the global context. However, such comprehensive studies in India are scarce, especially from a national perspective.

Although previous research has focused on mobile phones and various minerals stored in mobile phones, from a wide variety of countries and regions contexts, research on the present and future status of CHTMs stored in waste cellphones, which are essential for future clean energy transition and manufacture of high-end products, has been limited. Several studies highlight the Chinese scenario. For example, He et al. (2018) revealed the Chinese situation related to the present and future status of HTMs stored in waste mobile phones. To the best of our knowledge, no previous known study has been conducted to estimate the production and future trends of cellphones in India, including the differentiation between smartphones and feature phones. As the Indian cellphone market has been booming since 2009, it is rational to set 2009-2035 as the research time period. In this paper, we analyzed the generation of waste cellphones and the CHTMs stored in them in India from 2009-2035 based on the characteristics of different types of cellphones. The research supports CHTM recycling from waste cellphones to achieve a sustainable green supply of CHTMs and thus ensure the balanced development of the electronic industry in India. A reference could also be provided for other developing or developed countries.

This study aims to bridge the research gap by analyzing the volume of accumulated waste cellphones and the volume of CHTMs contained in them based on the differentiation between smartphones and feature phones and by predicting the future trends of CHTMs in waste cellphones in India. Moreover, a comparison of the trends and potential between China and India is conducted. The remainder of this article is structured as follows: Section 1 starts with the introduction and background of waste cellphone recycling. In Section 2, relevant methodologies are presented, together with the data source and data collection. Section 3 presents the results, and Section 4 provides a discussion of the results. We conclude the article in Section 5 with implications, limitations and future directions.

2 Methodology

2.1 Conceptualization

Material flow analysis (MFA) is an effective tool to analyze the flows and stocks of any material-based system (Brunner et al., 2016). In this study, the product life cycle includes the entire market life from initial market entry to final market exit, that is, the full "cradle-to-grave" process (Murakami et al.,2010; Oguchi et al., 2010). Waste cellphones refer to cellphones that have finished their entire service to users and do not re-enter the active-use stage. The average service years of cellphones are regarded as the cellphone lifespan.

Different countries classify CHTMs differently. For example, in China, CHTMs are composed of a variety of metals defined by the Ministry of Natural Resources and Key Laboratory of Strategic Studies, including 17 rare earth metals (He et al., 2020; He et al., 2018). In India, the minerals of rare metals, tantalum, tungsten, barium, cobalt, lithium, niobium, rubidium, cesium, tin, cadmium, mercury, molybdenum, and vanadium, in addition to nickel and zircon are regarded as strategic high-tech minerals (Randive et al., 2019).

Mineral resource availability has various definitions; in this study, it is defined as the secondary resource reserves of a particular mineral that might potentially be provided to society. The mineral value can be calculated via a specific economic and technical assessment system. This system considers some geological, economic and technological factors associated with mines or mineral deposits (He et al., 2018; Lu et al., 2009). In this study, the resource availability of various CHTMs refers to the social stocks of CHTMS.

2.2 System boundary

In this paper, the geographical boundary is limited to India. The system boundary of the waste cellphones' material flow process is shown in Fig. 1. The Indian telecommunication market includes two main categories of cellphones: smartphones and feature phones. The contents of CHTMs in the two categories differ considerably. As shown in the system boundary, CHTMs first come into the production procedure of cellphones as raw materials after being extracted and processed and remain in the cellphones during the active-use stage. At the end of the cellphone lifespan, CHTMs contained in these cellphones can be recycled or reused as secondary mineral resources to re-enter the manufacturing step. Thus, this process is a "cradle-to-grave" process.

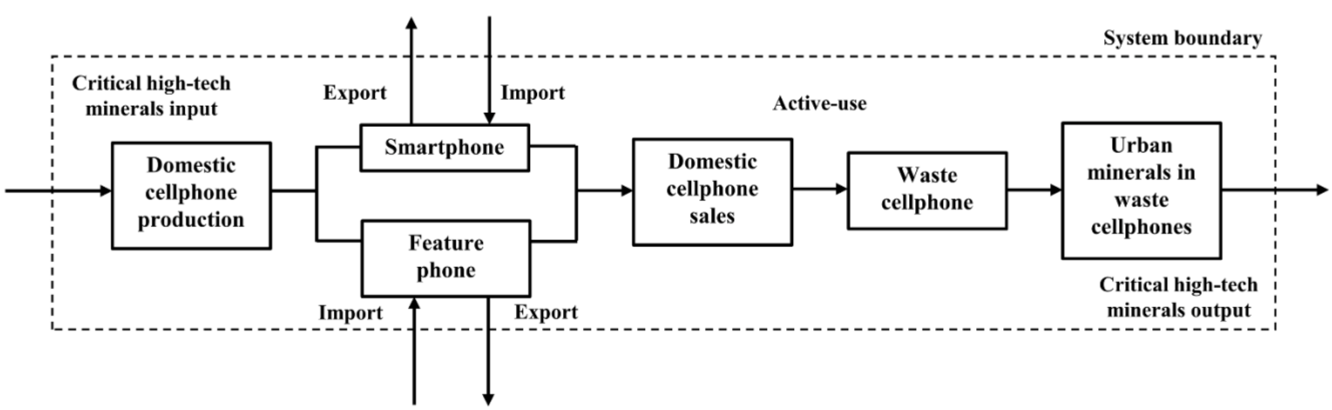

Fig. 1. System boundary of the material flow process of waste cellphones in India.

2.3 Distribution of cellphone lifespan

2.3.1 Estimation of waste cellphone generation

The Weibull distribution is commonly applied for product lifespan modeling, and many studies have used this distribution to estimate the lifespan of electronic and electrical products (Tasaki et al., 2004; Oguchi et al., 2008; Walk., 2009; Polák et al., 2012; Kalmykova et al., 2015; Zeng et al., 2015; He et al., 2018). In this study, the double-parameter Weibull distribution was adopted to analyze the cellphones' lifespan distribution throughout the designated years using Minitab 17.0 (Wang et al., 2016; He et al., 2018).

The probability density function $f(t)$ and distribution function $F(t)$ of the double-parameter Weibull distribution are shown in Equations (1) - (3):

$$F(t) = 1 - \exp\left[-\left((t-\gamma)/\delta\right)^{\beta}\right] \tag{1}$$

where the scale parameter is δ, the shape parameter is β, and the location parameter is γ. In this paper, $\gamma = 0$. Therefore,

$$\mathrm{F(t)} = 1 - \exp\left[-(\frac{t}{\delta})^{\beta}\right] \tag{2}$$

$$\mathrm{f}(t) = (\frac{\beta}{\delta})(\frac{t}{\delta})^{\beta-1} \cdot \exp\left[-(\frac{t}{\delta})^{\beta}\right] \tag{3}$$

$t \geq 0, \beta > 0$

where $F(n)$ represents the cumulative rate of obsolete generation in year *n*, and $f(n)$ represents the obsolete generation rate in year *n*. $F^{'}(\mathrm{n})$ represents the probability of obsolete generation throughout year *n*, which can be calculated from $F(n)$ to $F(n-1)$:

$$F^{'}(n) = \exp[-(\frac{n-1}{\delta})^{\beta}] - \exp[-(\frac{n}{\delta})^{\beta}] \tag{4}$$

The quantity of waste cellphones generated in year n, which is denoted by $P(n)$, can be estimated using $S(t)$ and $F^{'}(\mathrm{n})$. $S(t)$ represents the total quantity of cellphones that enter the market in year t.

$$P(1) = S(0) \cdot F^{'}(1)$$

$$P(2) = S(0) \cdot F^{'}(2) + S(1) \cdot F^{'}(1)$$

$$P(3) = S(0) \cdot F^{'}(3) + S(1) \cdot F^{'}(2) + S(2) \cdot F^{'}(1)$$

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Given these equations, Equation (5) can be transformed into the following format:

$$P(n) = \sum_{t=0}^{n-1} S(t) F^{'}(n-t) \quad (5)$$

where $P(n)$ represents the cumulative generation of waste cellphones.

2.3.2 Estimation of the social stock of critical high-tech minerals

The quantity of CHTMs contained in waste cellphones is determined using Equation (6) (Cucchiella et al., 2015):

$$Q_{\mathrm{t}}^{\mathrm{i}} = \mathrm{P}(\mathrm{n}) \cdot c_{\mathrm{i}} = \sum_{\mathrm{t}=0}^{\mathrm{n}-1} S(\mathrm{t}) \cdot F^{'}(n-t) \cdot c_{\mathrm{i}} \quad (6)$$

where $Q_{\mathrm{t}}^{\mathrm{i}}$ stands for the quantity of CHTM i produced in year t, $P(n)$ represents the quantity of waste cellphones in year n, and c_{i} is the content of CHTM *i* in each cellphone.

2.3.3 Future trends analysis

In this section, the prediction of future waste cellphone generation was conducted via the market supply method using Equation (7):

$$\hat{W}(t) = \sum_{i=1}^{t} \{S(t-i) \cdot f(i)\} \quad (7)$$

where $\hat{W}(t)$ represents the future generation of waste cellphones in year t, $S(t-i)$ denotes the sales of cellphones in year (t-i), and $f(i)$ represents the lifespan distribution function.

The future volume of CHTMs contained in waste cellphones is expressed by Equation (8):

$$\hat{V}_t^{\mathrm{i}} = \hat{W}(t) \cdot p_i = \sum_{i=1}^{t} \{S(t-i) \cdot f(i)\} \cdot p_i \quad (8)$$

where $\hat{V}_t^{\mathrm{i}}$ represents the amount of CHTM i contained in waste cellphones in year t, and p_i is the content of CHTM *i* in each cellphone.

2.4 Data source and collection

The data in this research were obtained from the websites of recycling companies, public literature, and industrial reports. The number of cellphones shipped was employed as a proxy for cellphone sales based on the assumption that "all cellphones in the market are likely to be sold every year". Although cellphones were first introduced in India from 1995–1996, they took a decade to become the dominant means of communication (Singh, S. K. 2008). The shipment information of two types of cellphones in India was obtained from International Data Corporation (IDC) bulletins (IDC, 2009–2019), and the average lifespan of cellphones in India was based on data from Stevens (Stevens, A., 2013). Specific content information regarding the CHTMs contained in different cellphones was obtained from previously published literature (Cucchiella et al., 2015; He et al., 2018), and the data scope of this study was restricted to India.

In projecting the sales of cellphones from 2020 to 2035, different categories of cellphones share some similarities but also distinct trends. However, the total cellphone shipments in 2020 are assumed to decline by 10% due to the Coronavirus Disease 2019 (COVID-19) pandemic

(Shilpi Jain, 2020). According to a global cellphone shipment prediction released by Canalys, the annual cellphone shipment growth rate will be -35.5%, -17.75%, and -8.88%, respectively, in 2020, 2021 and 2022. The shipment growth rate of feature phones and smartphones in India is assumed to be consistent with the global scenario (Canalys, 2020). Furthermore, we assumed that the impact of the pandemic will last for at least three consecutive years; in other words, the annual cellphone shipment growth rate will return to normal after 2022. For the feature phones, we utilized the 10-year average growth rate (3.86%) and calculated the data based on historical figures. We believe that this approach is a rational approach, as Mathapati et al. (2018) revealed that a large population in India is still using feature phones due to financial and skill constraints and will continue to use feature phones in future decades. With regard to smartphones, we applied a 2-year average growth rate (10.82%) due to dramatic fluctuation over the past 10 years. We assumed that these growth rates are stable and will remain steady until 2035.

The quantities of the two types of cellphones that were shipped are shown in Fig. 2. Minitab 17.0 was selected to model the shape (β) and scale (δ) parameters of the Weibull distribution. The lifetime information of the cellphones was obtained from previous studies and reports (Canalys, 2020; Stevens, A., 2013), and detailed information about the lifetime distribution of cellphones is shown in Table 1 and Fig. 3.

The various CHTMs contained in feature phones and smartphones in India are presented in Table 2 (Cucchiella et al., 2015; He et al., 2018).

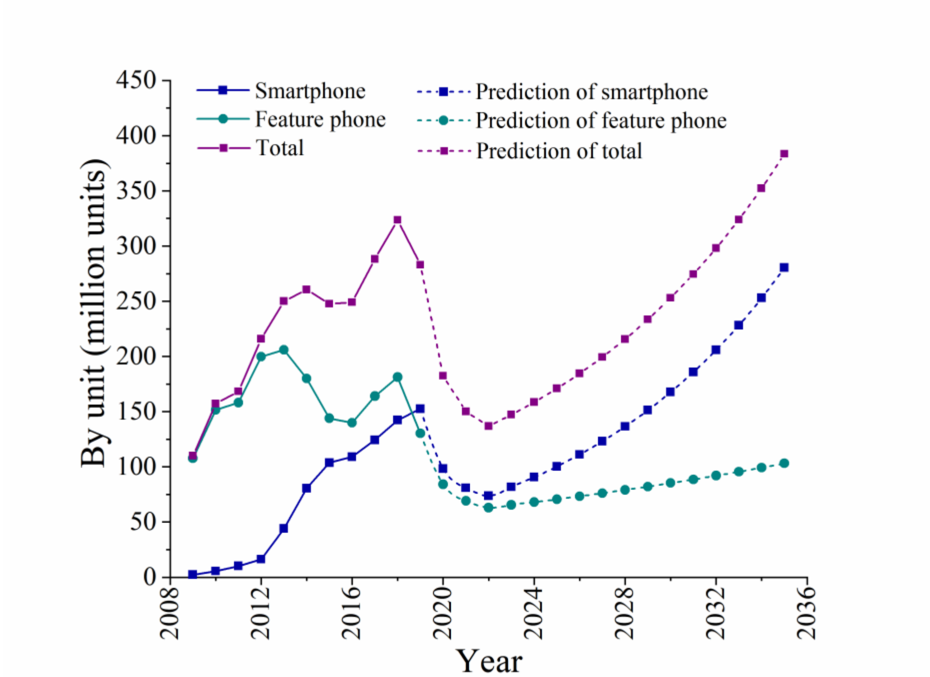

Fig. 2. Adjusted shipment number and future trends of waste feature phones and smartphones from 2009 – 2035.

Table 1 Parameters and formulas of the lifetime distribution for different cellphone categories

Cellphone Categories	Parameters	Formula
Smartphone	β=1.86 δ=9.53	f(t)=(1.86/9.53)(t/9.53)1.86-1exp[-(t/9.53)1.86] F(t)=1-exp[-(t/9.53) 1.86]
Feature phone	β=1.93 δ=7.31	f(t)=(1.93/7.31)(t/7.31)1.93-1exp[-(t/7.31)1.93] F(t)=1-exp[-(t/7.31) 1.93]

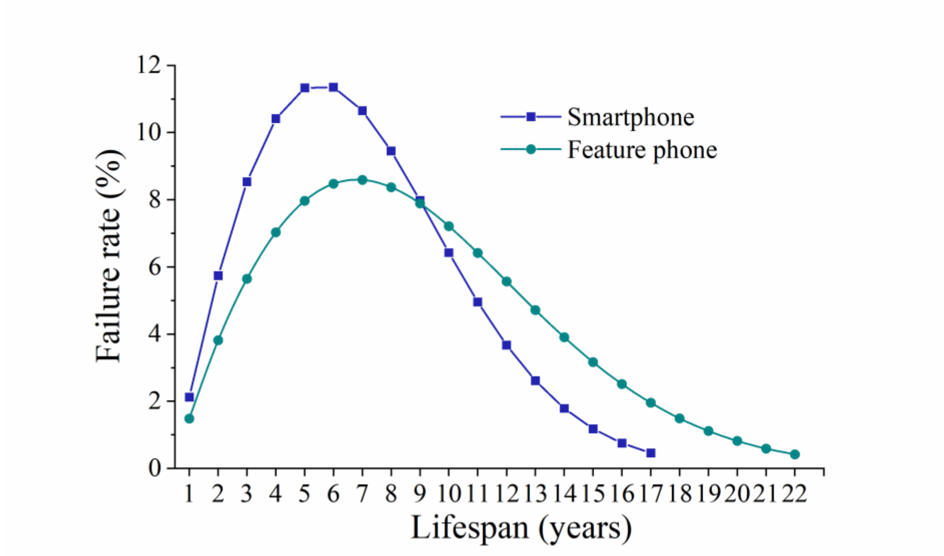

Fig. 3. Lifespan distribution of feature phones and smartphones.

Table 2 Critical high-tech minerals contained in feature phones and smartphones in India

Critical high-tech mineral categories	Product categories	
	Feature phone (g/unit)	Smartphone (g/unit)
Cobalt	3.800	6.300
Antimony	-	0.084
Beryllium	-	0.003
Palladium	0.009	0.015
Platinum	-	0.004
Praseodymium	-	0.010
Neodymium	-	0.050

2.5 Sensitivity analysis

In this study, a sensitivity analysis was conducted to identify factors that influence the estimation results. Five scenarios were considered to assess the sensitivity. “B” was employed to represent the basic scenario. Scenarios 1 and 2 were used to examine the influence of shorter and longer cellphone lifespans on the number of generated waste cellphones. Scenarios 3 and 4 were applied to validate the impacts of material compositions by reducing and increasing the baseline value by 10%. A detailed description of the sensitivity analysis is provided in the results section.

3 Results

3.1 Generation of waste cellphones

The volumes of waste cellphones in India from 2009 to 2035, which were estimated using Equations (1) to (5) discussed in the previous section, are shown in Fig. 4.

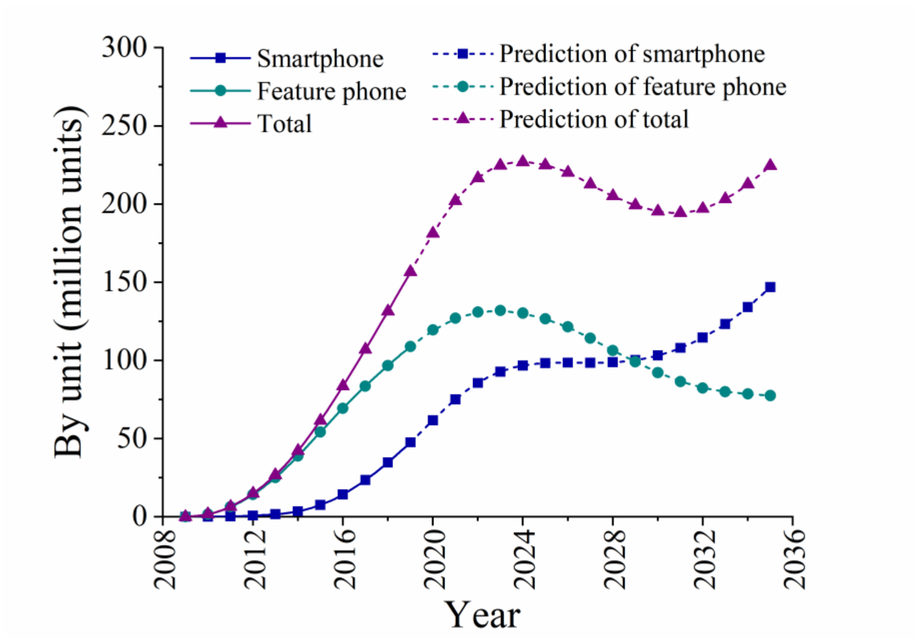

Fig. 4. Generation and future trends of waste feature phones and smartphones for 2009 – 2035.

Generally, the results indicate that waste cellphone development in India from 2009 to 2035 can be categorized into two periods, namely, the historical period and the future period. In the historical period, from 2009 to 2019, the quantity of waste cellphones displayed a rapid rise from nearly 1.65 million units in 2010 to approximately 157 million units in 2019, and the entire number of waste cellphones exceeded 632 million. In this period, approximately 134 million units of smartphones and 499 million units of feature phones accumulated. The results show similar trends for waste feature phones and waste smartphones but with slightly varying degrees.

Waste feature phones displayed an increasing process of “steady growth development”. The number of waste feature phones, which was approximately 1.6 million units in 2009, continuously increased to approximately 109 million units in 2019, which reveals a process of “gradual growth development”. The results show that in 2010, slightly more than 46,600 waste smartphones were produced; this number increased to 48 million by 2019.

In the future period, from 2020 to 2035, the generation of waste cellphones is projected to reach approximately 181 million units in 2020 and 224 million units in 2035, while the cumulative quantity of waste cellphones is predicted to exceed 3.34 billion units. During this period, the cumulative number of waste cellphones is expected to be approximately 1.7 billion feature phones and approximately 1.64 billion smartphones, which accounts for 51.02% of the total and 48.98% of the total, respectively.

The future developmental paths of smartphones and waste feature phones differ considerably depending on their service lifespans and adjusted or assumed annual growth rates. Generally, waste feature phones show a process of “moderate growth-decline”. The number of waste feature phones is predicted to increase steadily to a peak in 2023 of 132 million units. This quantity is expected to decrease gradually and ultimately reach 77.5 million units in 2035. The annual figure for feature phones is projected to fluctuate between 77.52 million units and 131.95 million units. However, feature phones are not expected to be phased out during this period. Conversely, waste smartphones exhibit a process of "moderate growth" only. The figure for smartphones is expected to increase from 61.73 million units in 2020 to 146.87 million units in 2035, which indicates that smartphones are predicted to grow steadily and continuously. Moreover, these figures indicate that the use of feature phones is decreasing but that of smartphones is increasing. Only in years near 2030 are the numbers similar, but the gap then continues to increase.

3.2 Estimation of critical high-tech minerals

As shown in Figs. 5 and 6, the CHTMs contained in waste cellphones were estimated; the results showed that more than 19.8 thousand tons of CHTMs were stored in waste cellphones in India from 2009 to 2035.

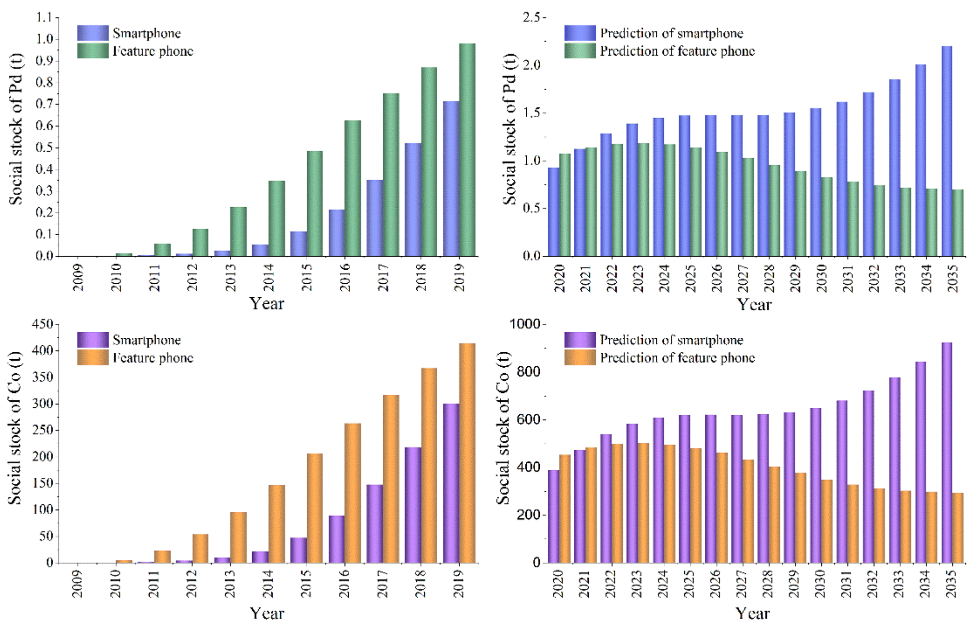

Fig. 5. Social stocks of high-tech minerals in waste feature phones and smartphones from 2009-2035. (palladium (Pd) and cobalt (Co)).

Specifically, Fig. 5 illustrates the social stocks of palladium and cobalt stored in waste cellphones from 2009 to 2035. These results are also categorized into two periods, namely, historical period and future period. In the historical period, from 2009 to 2019, the cumulative social stocks of palladium and cobalt contained in waste cellphones were approximately 6.5 tons and 2738.7 tons, respectively. In general, the social stocks of palladium and cobalt contained in both feature phones and smartphones and the sales of cellphones in this period increased steadily.

The total quantity of palladium and cobalt preserved in waste cellphones also increased substantially due to the steady increase in the sales of cellphones. The cumulative social stocks of palladium stored in waste cellphones in India surpassed 1.7 tons in 2019, which is equal to approximately 21.13% of the global palladium output — except Canada, Russia, South Africa, the United States, and Zimbabwe — which was approximately 8 tons according to data released by the United States Geological Survey (USGS., 2012). In India, the quantity of cobalt contained in waste cellphones exceeded 713.9 tons in 2019, which accounts for 22.84% of the cobalt stored in waste cellphones in China in 2016 (He et al., 2018). If the Indian government can take effective measures to properly reuse or recycle the CHTMs in waste cellphones, it is likely that the dependence on primary ore will be significantly reduced and the resource supply constraints relieved in India.

In the future period, with the increase in the production and consumption of various electronic products, the secondary resource effects of palladium and cobalt stored in waste cellphones will become increasingly apparent. From 2009 to 2035, the results show that the total quantity of palladium and the total quantity of cobalt stored in waste cellphones will be approximately 46.4 tons and 19,525.6 tons, respectively.

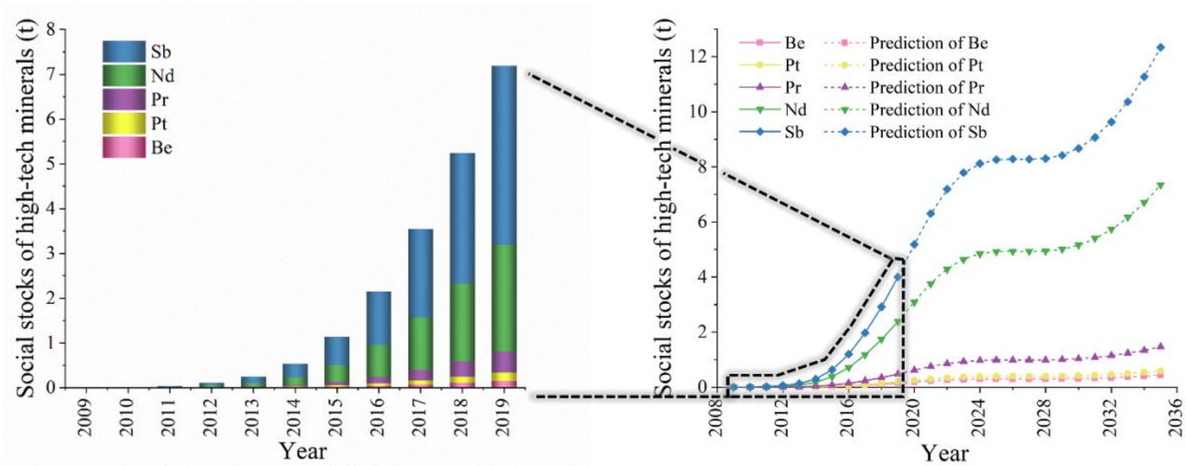

Fig. 6. Social stocks of high-tech minerals in waste smartphones from 2009-2035 (beryllium (Be), platinum (Pt), praseodymium (Pr), neodymium (Nd) and antimony (Sb)).

With technological advances and cellphone functional upgrades, a variety of CHTMs, such as antimony, beryllium, neodymium, praseodymium and platinum, which are not stored in feature phones, are currently being used to produce smartphones. The respective social stocks of these five CHTMs contained in waste smartphones from 2009 to 2035 are shown in Fig. 6. The results can be categorized into two periods, namely, the historical period and the future period. In the historical period, from 2009 to 2019, a total of 20.2 tons of these CHTMs accumulated in waste smartphones, including 11.2 tons of antimony, 0.4 tons of beryllium, 6.7 tons of neodymium, 1.3tons of praseodymium, and 0.5 tons of platinum. In 2019, the social stocks of beryllium, neodymium, praseodymium, platinum and antimony were 0.1 tons, 2.4 tons, 0.5 tons, 0.2tons and 4 tons, respectively. Efficient recycling and management of these CHTM stocks contained in smartphones would generate positive resource effects. An increasing amount of various secondary CHTM resources can be acquired if other CHTM-rich waste products are recycled appropriately and effectively.

In the future period, from 2020 to 2035, more than 247.1 tons of CHTMs are expected to be preserved in waste smartphones. Specifically, more than 137.5 tons of antimony, 4.9 tons of beryllium, 16.4 tons of praseodymium, 81.8 tons of neodymium, and 6.6 tons of platinum will be contained in waste smartphones. With the rapid advancement of artificial intelligence and future 5G-related infrastructure construction, it is foreseeable that increasingly diverse CHTMs will be accumulated or stored in future common waste electronic products, such as waste smartphones and laptops.

3.3 Sensitivity analysis

Estimation results always have some level of uncertainty. Assumptions were made regarding the proposed estimation at the beginning of the study. Sensitivity analysis is indispensable for estimation and future projection using mathematical models. It is highly recommended to investigate the uncertainty of the projection results in the assumed range of possible parameter values.

One important parameter that requires consideration is the cellphone lifespan distribution, which is a dynamic, undulating, and evolving value with the advancement of new technologies. The lifespan distribution is a major factor that influences the projection results of the number of waste cellphones that are generated, for both smartphones and feature phones. In this paper, the sensitivity of the mathematical model to parameters was analyzed in the Weibull distribution function with a range of ± 1.0 years. The estimated results for different cellphone lifetime assumptions in scenario 1 (7 years) and scenario 2 (9 years) are listed in the Supplementary Material. The average lifespan variation of ± 1.0 years causes a fluctuation in annual waste feature phone of approximately -3.21% to 1.52%. Assuming that the average lifespan of feature phones decreases to 7.0 years in scenario 1 and increases to 9.0 years in scenario 2, the average lifespan variation of ± 1.0 years will likely cause fluctuations of between approximately -3.21% and 1.52% in the annual number of waste feature phones that are generated. For smartphones, the average lifespan is assumed to decrease to 5.0 years in scenario 1 and increase to 7.0 years in scenario 2, which produces fluctuations of -6.93% and 6.85% in the future annual number of waste smartphones that are generated. The detailed estimation results of cellphones in different scenarios are shown in the Supplementary Material.

Material composition is another critical influencing factor. Components and metals will show different fluctuations according to the trends in technology renewal or cellphone updates. For example, the content of CHTMs in the different categories of cellphones appears significantly different. This analysis assumed that the average material content proportions are consistent when estimating the CHTMs in waste cellphones. This assumption is likely to lead to a deviation in the contents of CHTM quantities in different types of waste cellphones. Therefore, scenarios 3 and 4 considered different weights of CHTMs contents to conduct a sensitivity analysis. The detailed results of the sensitivity analysis in waste cellphones in different scenarios are presented in the Supplementary Material.

4 Discussion

4.1 Estimated quantities of waste cellphones

The sensitivity analysis shows that the cellphone lifespan is a key factor that influences the number of waste cellphones. Many previous studies have shown that the cellphone lifespan varies substantially among countries and regions. For example, Polák et al. (2012) discovered that the average lifespan of cellphones in the Czech Republic is approximately 7.99 years, which is longer than that in most countries. Araújo et al. (2012) found that the average lifespan of cellphones in Brazil is approximately 4.5 years, which exceeds the average according to experts. Rahmani et al. (2014) estimated that the average lifespan of cellphones in Iran is approximately 3 years. Yin et al. (2014) revealed that the average cellphone lifespan is less than three years in

China. Guo et al. (2017) reported that the average lifespan of cellphones is less than two years in China. One of the major reasons for these results is the distinctive consumer behavior in different regions and countries. However, the situation in the Indian context is intriguing. First, the popularity of smartphones is growing at a fast pace, and the majority of the Indian population appears to be interested in replacing old cellphones with the most up-to-date smartphones (Sharma et al., 2013). However, the e-waste disposal behaviors of Indian consumers varies dramatically in different parts of the country (Borthakur et al., 2019). The majority of the Indian population tends to use electronic products until they are damaged or new technology is available at an affordable price. Additionally, the informal economy is sizeable and contributes significantly to the long lifespan of mobile phones in India (Stevens, A, 2013). Therefore, the expected average lifespan of cellphones in India is much longer than that in most other countries and regions of the world. Studies show that mobile devices in India have the longest lifespan and can last six to eight years (Stevens, A, 2013).

To the best of our knowledge, few studies have estimated the generation and future trends of waste cellphones in India while considering the differences between feature phones and smartphones. Limited research studies focused on general waste electrical and electronic equipment (WEEE) products have been conducted for the Indian market. According to our estimation, during the period of 2009 to 2019, the total cumulative generation of waste feature phones and smartphones was approximately 498.9 million units and 133.8 million units, respectively. We further projected that from 2020 to 2035, the total cumulative waste generation of feature phones and smartphones will be approximately 1.7 billion units and 1.6 billion units, respectively. We believe that these results provide a solid basis and exert positive effects on waste cellphone management in India. However, the estimation accuracy would be greatly improved by data of better quality. We hope that in the near future, better data can be obtained for a thorough understanding of Indian cellphone consumer behavior to provide a more reliable estimation of the waste amount and a clearer interpretation of dynamic cellphone lifetime information.

4.2 Strategic value of high-tech minerals

With the trend of computerization, telecommunication and mobile phone technology innovation worldwide, the Indian electronics industry has become one of the fastest growing industries in the country (Agrawal et al., 2018). In particular, cellphones have become a near-necessary item in approximately a decade (Borthakur et al., 2019); they have become one of the fastest growing products in the electronics industry. CHTMs contained in cellphones have experienced dramatic changes during this period. In this study, when examining the availability of CHTMs in cellphone waste, the significant changes in the cellphone industry and the complexity of the CHTMs included in phones were fully assessed and considered.

CHTMs are pivotal raw materials for many global emerging industries. The demand for various CHTMs is expected to continue growing in the long term due to the rapid advancement of telecommunication and battery innovation. However, the stable and continuous supply of various CHTMs is likely to be affected by several factors. One factor is that the supply of CHTMs is greatly reliant on the particular carrier mineral. For example, the exploitation of gallium largely relies on the capacity of its carrier mineral, aluminum (He et al., 2018). Another important factor is unexpected world events or global emergencies. For instance, the recent outbreak of the COVID-19 pandemic has substantially affected global supply chains (Shin et al., 2020; Kilpatrick., 2020; Goetzen., 2020). In extreme circumstances, waste cellphones have become an abundant secondary CHTM reservoir with considerable strategic value. In India, the accumulated social stock of cobalt stored in waste cellphones surpassed 2738.7 tons in 2019 and is projected to exceed 16786.8 tons in 2035. Additionally, the grade of cobalt in waste cellphones is significantly higher than that in natural ore (Yu et al., 2010). A previous study revealed that only approximately 1.2 kg of cobalt material can be acquired from mining one ton of natural cobalt ore, but approximately 63 kg of cobalt can be detected in one ton of waste smartphones (He et al., 2018). Therefore, the proper handling and recycling of CHTMs in waste cellphones has significant strategic value.

4.3 Comparing India with China

China and India are currently the two largest active Internet markets (Borthakur et al., 2019); they generate an enormous quantity of waste electronics annually. Reports show that China and India are expected to double the generation of e-waste quantities in the next few years (Awasthi et al., 2017). Cellphones are one of the fastest growing categories of WEEE products in both the Chinese and Indian contexts.

In China, approximately 2.3 billion units of waste feature phones and 1.0 billion units of waste smartphones were generated from 1987 to 2016, and more than 15 thousand tons of CHTMs could be recycled from these waste cellphones. In the future, the generation of more than 1 billion units of waste cellphones is expected in 2035, which will create over 90 thousand tons of CHTM preservation (He et al., 2018).

According to our estimation, the accumulated number of waste cellphones in India has surpassed 632.7 million units, including approximately 499 million units of waste feature phones and 133.8 million units of waste smartphones from 2009 to 2019. Moreover, more than 2765.4 tons of CHTMs could be recycled from these waste cellphones. Forecasting indicates that the generation of waste cellphones is projected to be 181.2 million units in 2020 and to reach 224.4 million units in 2035, with more than 17,073.8 tons of CHTMs.

As previously discussed, in terms of the present and future availability, an extraordinary number of waste cellphones are available in China and India, and a large quantity of CHTMs is stored in cellphone waste, which represents an abundant secondary CHTM reservoir. Notably, in future decades, the generation of waste feature phones is expected to decrease rapidly in China; however, the situation in India is entirely different. In 2035, it is predicted that more than 99% of waste cellphones in the Chinese market will be smartphones, and the percentage of waste feature phones will be less than 1%. Feature phones will still have an important role in the Indian cellphone market. One possible reason for this situation is that the majority of the Indian population is still facing constraints in upgrading their feature phones to smartphones (Mathapati et al., 2018). A detailed graphic comparison of India and China is included in the Supplementary Material.

Future relevant studies can be conducted based on other countries' datasets using the methodology utilized in this study. For example, our results can be extended to other developing countries, such as Brazil, Mexico, Vietnam, etc. A more comprehensive comparison of these emerging countries could reveal useful patterns of cellphone recycling and help to identify the proper cellphone managerial strategies. Most importantly, this broader comparison would contribute greatly to other countries' cellphone strategic planning.

5 Conclusions and Implications

5.1 Concluding remarks

The aim of this study was to estimate the past volumes and predict the future volumes of waste cellphones and various CHTMs contained in them in India from 2009–2035. No previous study has calculated the number of cellphones and future trends of cellphones in India. In this study, material flow analysis and the Weibull distribution were employed to estimate the quantity of waste cellphone generation and associated CHTM stocks by separately considering smartphones and feature phones. Since India became the second-largest smartphone market after China, it is important to study the current status and future trend of the cellphone market in India. This article provides baseline data to fill the knowledge gap and to help stakeholders enhance their understanding of this field.

Based on this analysis, the following conclusions can be reached: (1) Waste cellphones contain various CHTMs, and the contents of CHTMs varies between smartphones and feature phones; (2) From 2009 to 2019, the accumulated number of waste cellphones in India surpassed 632.7 million units, including approximately 130 million units and 500 million units of waste smartphones and feature phones, respectively. More than 27 thousand tons of CHTMs are available for recycling. In the future, it is predicted that more than 180 million units of waste cellphones will be generated in 2020. This number will exceed 220 million in 2035, which creates more than 170 thousand tons of CHTM preservation in waste cellphones. (3) Cellphone waste volumes in India show a general upward tendency, which indicates that various potential CHTMs contained in cellphone waste should be appropriately reused or recycled.

5.2 Implications

Based on the results, several recommendations can be made to help improve waste cellphone management in India: (1) From a government perspective, the Indian government should propose a comprehensive package plan to improve relevant WEEE recycling laws and regulations, focusing especially on waste cellphone recycling. First, the cellphone recycling industry should be formulated and regulated since the primary e-waste recycling method in India is informal, which is harmful to the environment and human health. Second, the Indian government should recognize the strategic importance of various CHTMs contained in waste cellphones, which comprise an abundant potential HTM reservoir that is critical for national security. Third, the Indian government should implement policies regarding a circular and sustainable WEEE recycling system and invest federal funds to support online WEEE recycling activities. (2) From a company perspective, various cellphone companies should make efforts to address this situation. First, the product ecological design should be enhanced by manufacturing companies to ensure that future waste cellphones can be dismantled or reused with a standard form. Research-based companies should invest sufficient funds into research and development (R&D) to improve dismantling or refining technologies. Second, domestic companies should attract foreign investments. With some in-depth operations among stakeholders, encouraging companies to actively collect waste cellphones and handle waste cellphones appropriately will have long-term benefits. (3) From a consumer perspective, local consumers have enormous potential for improvement. Consumers' consciousness, awareness, recognition and attitude will directly and indirectly affect their behavioral habits. First, Indian consumers should improve their awareness of waste mobile phone recycling and actively transition from the traditional approach to an approach supporting environmental protection and efficiency. Second, actual cellphone consumption behaviors can be transformed by changes in consciousness. Moreover, if the majority of consumers in society were voluntary role models, the end-of-life recycling rate would likely improve.

5.3 Limitations and future directions

This study aims to analyze the volume of accumulated waste cellphones and the volume of the CHTMs contained in these cellphones by separately considering feature phones and smartphones in the Indian context. Moreover, a market supply model was adopted to predict the future trends of CHTMs in waste cellphones in India. However, there are still some limitations and uncertainties in this article due to limited resources, such as time and data availability. First, the cellphone lifespan information was obtained from previous publications and may not be valid for India. Second, our estimation and prediction results are theoretical. Although the results are based on a universally acknowledged mathematical model, they might still exhibit some deviations. Moreover, the material composition may shift over time; however, we used fixed values reported in the literature because accurately projecting future changes is nearly impossible. Last, more data should be provided to analyze the impact of the source and supply of strategic metals on cellphones from the perspective of the upstream and downstream industries of strategic minerals in cellphones. Considering these limitations, future studies should conduct a national questionnaire survey to directly obtain first-hand cellphone lifespan information from Indian cellphone consumers. Additionally, future studies should also consider the designs of next-generation cellphones, which will likely have different CHTM compositions.

Acknowledgments

This research was financially supported by the National Social Science Foundation of China (18ZDA061), National Natural Science Foundation of China (71991482), National Natural Science Foundation of China (42071276), National Social Science Foundation of China (14ZDB136), China Scholarship Council (201706370234), and Innovation Project Foundation of Central South University (2018zzts097).

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