Impact of technological innovation and regulation development on e-waste toxicity: a case study of waste mobile phones

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Technology innovation has accelerated progress in Information and Communications Technology (ICT), especially in the mobile phones sector. Concurrently, local, national, and international governments are enforcing stricter regulations to protect natural resources and human health. The paper attempts to address the question: Have technological innovations and regulation development had a positive impact on ecosystems and public health? We identified 36 waste mobile phones (WMPs) manufactured between 2002 and 2013, assessed their metals concentration, leachability, and potential impact on environment and human health using digestion, Toxicity Characteristic Leaching Procedure (TCLP), and USEtox model, respectively. The results highlight that regulations did not have significant impact on total metal content, except some heavy metals, while technology innovation recorded stronger impact. WMPs should be classified as hazardous due to excessive lead content. Copper posed the most significant ecotoxicity risk, and chromium showed the most significant risk for both cancerous and non-cancerous diseases. Additionally, we demonstrated that WMPs toxicity increased with technology innovation.

The first mobile phone invented by Marty Cooper 44 years ago, weighed 2.5 pounds, was 9 inches in length, 5 inches in thickness, required ten hours to charge, and functioned for 20 minutes1. Today, mobile phones are versatile and work like professional computers and cameras; are much lighter, compact, beautiful, and intelligent; and have become an indispensable part of human lives2. Accelerated innovation has lead to proliferation in mobile phone production. International Telecommunication Unions3 reported that 781 million mobile phones were generated in 2015 and the numbers will increase to 877 million units by 2020. However, rapid innovation has also reduced the usage span of phones4, resulting in increase in the number of waste mobile phones (WMPs), categorised as waste electric and electronic equipment (WEEE), also called as electronic waste or e-waste5,6. WMPs and waste printed circuit boards (WPCBs) are listed as one of hazardous wastes by the U.S., European Union, China, and other nations7–9.

E-waste is the core of “urban mining” due to abundant content of secondary materials, especially valuable metals such as copper, gold, and palladium10,11. Gold contained in WMPs is higher than other e-waste. For example, gold in WPCBs of WMPs is 300 g per ton compared to 100 g per ton found in WPCBs of desk computers12. Consequently, WMPs can be considered as the core of e-waste. At present, recovery, reuse, and recycling are considered as the most effective approaches to WMPs management13. However, only 10% of the end-of-life mobile phones are recycled in the U.S.; the residual 90% are stored at homes by users or are dumped in landfills14, where they leach toxic substances into the environment and threaten the ecosystem and human health15,16.

Toxic substances including heavy metals such as lead, zinc, chromium, cadmium, and brominate flame retardants like PBBs and PBDEs threaten the ecosystem and human health, especially when treated improperly17,18. Although regulations vary across countries, they are increasingly stricter due to environmental and public health concerns19. In the past 20 years, local, national, and international governments have enacted series of regulations and laws to restrict the use of hazardous materials in information and communication equipment20. The best examples are the “Directive on the restriction of the use of certain hazardous substance in electrical and electronic
Metals and hazardous assessment.

Sample preparation. In 2014, we conducted internet searches and identified nearly 1000 mobile phones models produced from 2000 to 2013. We chose one mobile model produced by the top three or four manufacturers each year. The top manufacturers were mainly NOKIA, SAMSUNG, MOTOROLA, BLACKBERRY, and APPLE. Thus, we identified 52 mobile phones manufactured between 2000 and 2013, which are listed in Supporting Information (SI) - Table 1. Subsequently, we searched the market and several mobile phone recycling companies to collect all identified WMPs. We collected 36 WMPs over one and a half years, though some were broken, short of battery, or lacked back shells. Detailed information about the 36 cellular phones is given in SI Table 2. We classified WMPs into two categories: Group 1 - without any physical parts missing; and Group 2 - without battery or back shell, as detailed in SI Table 2.

All WMPs were weighed, disassembled, and crushed using a mill (SM-2000, Retsch, Germany) to particles of diameter around 9.5 mm for TCLP (Toxicity Characteristic Leaching Procedure, U.S.E.P.A. 1992) testing. The obtained powder samples were stored in marked airtight polyethylene bags for further analysis.

Metal analysis and hazardous test. HF-HClO4-HNO3 system was used to digest the powder samples, as described elsewhere. The metals in the digested solutions were analyzed using inductively coupled plasma-optical emission spectrometer (ICP-OES, Perkin Elmer, Optima 8300, USA). In this research, 22 elements were measured in the WMPs: aluminium, arsenic, antimony, barium, beryllium, cadmium, chromium, cobalt, copper, gold, iron, magnesium, molybdenum, lead, nickel, palladium, selenium, silver, thallium, tin, vanadium, and zinc. Sample preparation was done using a high frequency plasma-sprayer (Ethos, Foss Tecator, Sweden) and a microwave digestion system (MDS, Milestone, Italy). The digested solution was analyzed using an inductively coupled plasma-optical emission spectrometer (ICP-OES, Perkin Elmer, Optima 8300, USA). The results were compared with the limits in the WEEE Directive.

Life cycle impact assessment using USEtox. USEtox is a scientific environment model used to characterize potential impact of toxic chemicals in products on human toxicology and ecotoxicology. The model outputs the environmental fate, effect parameters, and also improves understanding and management of chemicals in the global environment by further applying the model to describe the exposure and effects of chemicals. It was developed under the auspice of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC). The researchers continue to update the model and factors of USEtox which updated from Version 1.01 (2010) to Version 2.02 (2016). In this study, we chose the USEtox “mid-point effect” characterization approach rather than the “end-point effect” in Version 2.02, which minimizes inference of data and uncertainties caused by interactions between different impacts. The potential carcinogenic and non-carcinogenic impacts of human toxicity and eco-toxicity of the selected metals were calculated according to the formula:

\[ P_x = C_x \cdot W \cdot Wf_x \]  

where, \( P_x \) represents the impact score of metal \( x \) in the WMP; \( C_x \) is the concentration of metal \( x \) in the WMP (kg/kg, Table 1); \( W \) is the total weight of the sample (kg, SI Table 2); and \( Wf_x \) is the characterization factor for the corresponding potential of metal \( x \). The units of the characterization factor for human toxicity and ecotoxicity were cases/kgsubstitution and PAF-m^3-day·kg^-1, respectively. The characterization factors derived from USEtox were associated with the impacts of metals emitted to household indoor air, industrial indoor air, urban air, rural air, fresh water, sea water, natural soil and agricultural soil.

Results and Discussion

Metals and hazardous assessment. Metals contained in the 36 WMPs are listed in Table 1. The sum of the 22 metals in the WMPs accounted for 8.94–30.63% of the total, consistent with previous studies. Iron was the most abundant metal (ranging from 2552 to 52765 mg/kg, with an average of 34335 mg/kg), representing about 20% of the total metallic content mainly because of the steel shell. Copper (ranging from 20438 to 37472 mg/kg, with an average of 28351 mg/kg) and aluminium (ranging from 7276 to 62363 mg/kg, with an average of 27567 mg/kg) ranked next, at similar percentages of about 16% of the total. Copper is primarily used within the printed wiring board (PWB) to facilitate electrical connection between miscellaneous layers in the phone board. Aluminium is mainly present in the batteries of the WMPs as a current collector, PWBs, and shells for lowering weight. Chromium and nickel levels ranked from 233 to 77687 mg/kg and 2225 to 52765 mg/kg, representing about 10% of the total. Silver, lead, and barium were also important metals in the WMPs, as described elsewhere. The metals in the digested solutions were analyzed using inductively coupled plasma-optical emission spectrometer (ICP-OES, Perkin Elmer, Optima 8300, USA). In this research, 22 elements were measured in the WMPs: aluminium, arsenic, antimony, barium, beryllium, cadmium, chromium, cobalt, copper, gold, iron, magnesium, molybdenum, lead, nickel, palladium, selenium, silver, thallium, tin, vanadium, and zinc.

In the digested solutions, we measured the following elements: aluminium, arsenic, antimony, barium, beryllium, cadmium, chromium, cobalt, copper, gold, iron, magnesium, molybdenum, lead, nickel, palladium, selenium, silver, thallium, tin, vanadium, and zinc. The results were compared with the limits in the WEEE Directive.

The TCLP (Method 1311), which is designed to determine the mobility of chemical substances in liquid, solid, and multiphase wastes, is widely used in research to test potential hazard levels. Six elements including arsenic, barium, cadmium, chromium, lead, and silver were tested in the WMPs using the TCLP.
54438 mg/kg, with averages of 22112 mg/kg and 16915 mg/kg, and comprised nearly 12.83% and 10% of the total, respectively. Other metals in the ranges of 1–10% were zinc (ranging from 101 to 172783 mg/kg, average of 33103 mg/kg), tin (ranging from 900 to 11384 mg/kg, average of 5137 mg/kg), and barium (ranging from 432 to 15711 mg/kg, average of 2385 mg/kg), constituting about 7.73%, 6.26%, 5.45%, 2.98%, and 1.38%, respectively. The rest including arsenic, gold, molybdenum, lead, palladium, silver, selenium, thallium, and vanadium, which were at least one order of magnitude lower, and were at levels lower than 1%. Beryllium and cadmium could not be detected in any of the investigated WMPs.

The results of the TCLP tests are presented in Table 2. TCLP leaching concentrations of almost all the tested metals were far below their thresholds, except for lead of some models which exceeded the threshold of 5 mg/L. Five of the 36 TCLP lead leaching concentrations, namely, from the NOKIA 7650, MOTO V70, SAMSUNGD508, BLACKBERRY 9900, and IPHONE 5 models, exceeded the limit, at 10.43, 23.78, 19.69, 5.24, and 10.37 mg/L, respectively. Therefore, those five models were classified as hazardous waste.
Potential environmental and human health impact assessment. Data obtained from chemical analysis of the cellular phones from 2002–2013 were used with the base data and modelled using USEtox. The results are shown in Fig. 1. Copper posed the most significant ecotoxicity risk (ranging from 52344–123937 PAF·m·day·kg\(^{-1}\)), followed by aluminium (ranging from 18236–81096 PAF·m·day·kg\(^{-1}\)), and nickel (10047–30070 PAF·m·day·kg\(^{-1}\)) which also posed considerable risks. Similar results were also recorded for WPCBs, where copper posed the most significant ecotoxicity risk 7, ranging from 13273–28153 PAF·m·day·kg\(^{-1}\). The two differed in the proportion of copper's potential ecotoxicity impact, which was about 58% in WMPs but almost 90% in WPCBs. In addition, zinc ranked second for ecotoxicity risk of WPCBs, and the rest were insignificant7. Aluminium and nickel ranked second for WMPs as discussed before. This can be attributed to the differences in composition (as shown in Table 1).

Chromium, mainly found in screens, plastics, and shell of alloy steels 21, exhibited similar tendency for both cancer and non-cancer diseases and showed the most significant risk, ranging from 1.16 × 10\(^{-3}\) to 2.57 × 10\(^{-4}\) cases/kg\(_{emitted}\) and from 1.11 × 10\(^{-4}\) to 2.46 × 10\(^{-4}\) cases/kg\(_{emitted}\) respectively. Chromium for cancer risk weighed almost 98% of the total, and was about 77% for non-cancer risk. The risk potential of zinc (ranging from 1.01 × 10\(^{-5}\) to 2.82 × 10\(^{-5}\) cases/kg\(_{emitted}\)), an order of magnitude lower, and silver cannot be neglected. The potential human health risks, both cancer and non-cancer related, are significantly different compared to the results of WPCBs, where lead followed by nickel posed the most significant cancer risk, and zinc followed by lead for

### Table 2. Leachates from waste mobile phones according to the Toxicity Characteristics Leaching Procedure (TCLP). Note: N.D.: not detected; concentrations in bold are above regulatory limits; unit of measurement is mg/L.

| Year of production | Model            | Ag   | As   | Ba   | Cd   | Cr   | Pb   |
|-------------------|------------------|------|------|------|------|------|------|
| 2002              | NOKIA 7650       | 0.061| N.D. | 0.962| N.D. | N.D. | 10.430|
| 2002              | MOTO V70         | 0.031| N.D. | 1.472| N.D. | 0.014| 23.780|
| 2003              | NOKIA 1100       | 0.051| N.D. | 1.468| N.D. | 0.004| 0.820 |
| 2004              | NOKIA 7610       | 0.047| N.D. | 3.003| N.D. | 0.024| 2.155 |
| 2004              | MOTO V3          | 0.058| N.D. | 0.924| N.D. | 0.050|      |
| 2005              | SAMSUNG D508     | 0.061| 0.006| 1.480| N.D. | 0.005| 19.690|
| 2005              | NOKIA N90        | 0.046| N.D. | 0.576| N.D. | 0.028| 0.285 |
| 2005              | SONY ERICSSON K750c | 0.053| 0.177| 1.776| N.D. | 0.021| 0.224 |
| 2006              | NOKIA 5200       | 0.048| 0.012| 1.901| N.D. | 0.020| 2.216 |
| 2006              | SAMSUNG GH1-D908 | 0.060| N.D. | 1.806| N.D. | 0.175|      |
| 2006              | SONY ERICSSON W700C | 0.046| N.D. | 1.840| N.D. | 0.181| 0.182 |
| 2006              | MOTO A1200       | 0.025| N.D. | 2.855| N.D. | 0.022| 0.830 |
| 2007              | IPHONE 1         | 0.065| N.D. | 1.635| N.D. | 0.085| 0.014 |
| 2007              | NOKIA N95        | 0.062| N.D. | 2.780| N.D. | N.D. |      |
| 2008              | NOKIA E71        | 0.030| N.D. | 1.770| N.D. | 0.065| 0.170 |
| 2008              | BLACKBERRY 9000  | 0.047| N.D. | 2.325| N.D. | 0.023| 0.781 |
| 2008              | SAMSUNG i908E    | 0.058| N.D. | 0.430| N.D. | 0.004| 0.065 |
| 2008              | IPHONE 3G        | 0.061| N.D. | 1.628| N.D. | 0.023| N.D.  |
| 2008              | GOOGLE G1        | 0.061| N.D. | 1.669| N.D. | N.D. |      |
| 2009              | NOKIA N980       | 0.054| N.D. | 1.274| N.D. | 0.024| 0.043 |
| 2009              | SAMSUNG S5230    | 0.061| 0.014| 1.799| N.D. | N.D. |      |
| 2009              | IPHONE 3GS       | 0.048| N.D. | 1.033| N.D. | 0.042| 1.416 |
| 2010              | SAMSUNG Galaxy S | 0.060| N.D. | 1.778| N.D. | N.D. |      |
| 2010              | IPHONE 4         | 0.055| N.D. | 0.407| N.D. | 0.027| 0.630 |
| 2011              | BLACKBERRY 9900  | 0.049| N.D. | 1.039| N.D. | 0.102| 5.239 |
| 2011              | IPHONE 4S        | 0.055| N.D. | 0.375| N.D. | 0.028| 4.284 |
| 2011              | SAMSUNG Galaxy Note | 0.062| N.D. | 0.873| N.D. | N.D. |      |
| 2011              | GOOGLE Nexus 5   | 0.060| N.D. | 0.728| N.D. | N.D. |      |
| 2012              | SAMSUNG Galaxy Note II | 0.061| N.D. | 1.677| N.D. | N.D. |      |
| 2012              | IPHONE 5         | 0.062| N.D. | 0.695| N.D. | 0.059| 10.370|
| 2012              | SAMSUNG galaxy Nexus | 0.061| N.D. | 1.191| N.D. | N.D. |      |
| 2012              | BLACKBERRY 9850  | 0.062| 0.007| 1.875| N.D. | 0.018| 0.188 |
| 2012              | GOOGLE Nexus 4   | 0.061| N.D. | 1.179| N.D. | N.D. |      |
| 2013              | SAMSUNG Galaxy Note3 N9000 | 0.047| N.D. | 0.485| N.D. | 0.030| 0.613 |
| 2013              | GOOGLE Nexus 5   | 0.061| N.D. | 1.187| N.D. | N.D. |      |

| TCLP limit        | 5     | 5     | 100   | 1     | 5     |
| Detection limit   | 0.007 | 0.053 | 0.004 | 0.0027| 0.0071| 0.042 |
non-cancer risks. Similar results were obtained for WMPs by Hilbert and Ogunseitan, where nickel followed by chromium registered the most significant cancer risks; and beryllium followed by lead for non-cancer risks. This can be attributed to the fact that the characterization factors of hexavalent chromium in USEtox Version 2.02 is much higher than that of USEtox Version 1.01, which highlights the potential risk of chromium.

**Technology innovation and regulation development.** **Metals.** Two milestones, namely, the launch of full touch-screen smart phones in 2007 by APPLE and RoHS implementation by the European Union in 2006, were used to discuss the influence of technology innovation and regulation development on toxicity evolution of WMPs. Figure 2 illustrates integrated metal contents in the WMPs. Figure 3 indicates the potential impact of metals on ecotoxicity and human toxicity.

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**Figure 1.** Results of USEtox chemical life cycle assessment of eco-toxicological (a), human carcinogenic (b), and non- carcinogenic (c) impacts of metals in waste mobile phones.

**Figure 2.** Total metal content in 36 waste mobile phones from 2002 to 2013.
Figure 2 reveals that the total metal content in the WMPs initially increased from 125,073 in 2002 to 237,316 mg/kg in 2007 and then decreased to 174,745 mg/kg in 2013. It is evident that regulations did not have any notable impact on the total metal content in the WMPs. However, the concentrations of some heavy metals, such as lead (restricted by RoHS in 2006) registered significant decline in 2006, consistent with our previous research and others. Technology innovation registered a much stronger impact on total metal concentration, which increased from 2002 to 2007 because of functional demands and the uncertainty of future development of mobile phones until the emergence of APPLE's IPHONE in 2007, which reinvented mobile phones. The impact decreased after 2007 as technology advances after 2007 were used to perfect the blueprint of IPHONEs and limit costs. Therefore, this could guide the production to reduce environmental problem caused by electronic products.

Total metal contained in the Group 2 WMPs (SI Fig. 1) showed the same tendency as Fig. 2, while Group 1 WMPs (SI Fig. 2) appeared to increase from 2002 to 2006 and was stable at around 200,000 mg/kg. After 2006, Group 1 WMPs were mainly from the IPHONE series, and appeared to have two-year cycles: the first year for improvement in technology and the second year for improvement in the software system. Thus, we noted corresponding increase in the total metal concentration in the first year and decrease in the second. Therefore, we concluded that technology innovation had significant impact. Contrarily, regulations barely had an impact.

Technology innovation and regulation development sometimes show associated impacts for specific metals. For example, lead is used as tin-lead solders to attach various components to the PWB in mobile phones. Following its restriction in 2006, and subsequent substitution by silver, silver concentrations in the WMPs should significant increased after 2006. However, we observed that silver concentrations in the WMPs
decreased since 2005 (Table 1). This is maybe evidence that other technologies eliminating silver usage for connection were being innovated, reducing the metal content, especially of precious metals. Another example is antimony, which should have increase during the assessment period, as brominated flame retardants were restricted and other flame retardants required Sb2O3 as an auxiliary fire-resistant agent. However, antimony levels decreased from 623 mg/kg in 2008 to 167 mg/kg in 2013. A possible explanation could be the innovation of environment-friendlier auxiliary fire-resistant agents.

Technology innovation indicated significant impact on single metals. For example, nickel, zinc, molybdenum, iron, and chromium (SI Fig. 3), showed trends that were similar to the total metal contents (Fig. 2) and Group 2 WMPs. Strong evidence could be found in cobalt, magnesium, and vanadium, which increased over the years (SI Fig. 3). Cobalt is the main constituent of batteries, whose numbers increased due to energy demands, especially after the launch of IPHONEs. Magnesium increased from 1302 mg/kg in 2002 to 14157 mg/kg in 2013, which was due to the demand of stylish, portable, and lighter mobiles. This can also explain the slight increase in aluminium, and partly of vanadium, as they are used as alloy metals in steel and in batteries. For WPCBs, an increase in cobalt and vanadium attributable to technology innovation was also indicated by a previous study.

An interesting observation was that the concentrations of some metals or the sum of some precious metals remained at certain values regardless of the advances in technology innovation and regulation development. As shown in SI Fig. 4, copper was around 28,000 mg/kg during 2002–2013. In comparison, copper levels decreased with advancement in technology innovation in WPCBs. Some researchers have reported that copper in WMPs was increasing over the years though only samples of 2002, 2005, and 2009 were chosen. Besides, the sum of average concentrations of gold and palladium in WMPs were in the ranges of 80–100 mg/kg regardless of the brands and year of manufacture, as shown in SI Fig. 5. This is interesting, though other reports showed that precious metals decreased because of technology innovation. For example, Chen reported that technological innovation caused a decline in the use of gold in WPCBs, for cost-effectiveness; Charles found that the levels of gold was stable from 1991 to 2008, but palladium registered 80% reduction in RAM modules of WEEE.

**Potential ecotoxicity and human toxicity.** The overall trends of potential ecotoxicity and human toxicity displayed diverse increasing trends under the influence of technology innovation and regulations, as shown in Fig. 3. Total ecotoxicity of all the investigated metals increased over the assessment period. Total potential human toxicity of all the investigated metals, for cancer and non-cancer risks, registered a “three step” change: levels in 2002–2006 were at the lowest step, and increased sharply to the highest step in 2007–2009; and finally decreased to the middle step in 2010–2013. This means that the integrated potential toxicity of WMPs increased irrespective of the number of technology innovations and regulations. This result is disappointing as it is very difficult to enact regulations that protect the environment and human health. For example, China took ten years to implement the Chinese WEEE regulation in 2011, though these efforts are not yet to achieve the desired results. This is different to the potential environment and human health impact analysis of WPCBs, where both ecotoxicity and human toxicity showed declining trends with time, indicating that technology innovation and regulation development had positive effects on the environment and human health though the toxicity of some metals such as chromium increased with time. Besides, this implies that the priority of technology innovation is market focus or profitably and not toxicity risk reduction. Technology innovation is a key point in an economic growth engine, meanwhile, economic growth increases the use of technology. Thus, there is an urgent need to balance business profit with environmental benefits.

Toxicity evolution was similar to their corresponding metals concentration as toxicity characterization factors for each metal is specific. Copper was the only exception, as both its ecotoxicity and human toxicity, increased during the assessment period although its concentration remained nearly constant. This is because toxicity is also proportional to metal weight (Equation (1)), and copper weight in the investigated WMPs increased slightly.

**Conclusions**

This research demonstrates that WMPs continue to pose considerable threat to ecosystems and public health due to excess toxic metals. Regulation development had positive influence on reducing hazardous risks of a few specific toxic substances such as lead. New materials that are introduced by technology innovation before sufficient assessment exist risks according to our research where ecotoxicity and human toxicity of WMPs increased in the investigated period. This research strongly calls upon the consumers to urge the ICT industry undertake product toxicity risk elimination as their first priority in technology innovation. Additionally, governments at different levels should educate public concerns on sustainability, environment, ecosystem and public health and enable public monitoring the communication industry.

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Author Contributions
Y.C. designed and performed the experiments, analyzed the data and wrote the manuscript. M.J.C. designed the experiments, analyzed the data and wrote the manuscript. Y.G.L. contributed to the statistical analysis. B.W. provided help on test. S.C. contributed to the statistical analysis. Z.H.X. interpreted the date. All the authors discussed the results and commented on the manuscript.

Additional Information
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