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Solving the e-waste problem

StEP

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Solving the e-waste problem: An interdisciplinary compilation of international e-waste research

Edited by Deepali Sinha Khetriwal, Claudia Luepschen and Ruediger Kuehr

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Preface

"Societies which have reduced to a sustainable level the e-waste related burden on the eco-system that results from the design, production, use and disposal of electrical and electronic equipment", is the succinct commonly agreed on vision of the more than 55 institutional members of the Solving the E-waste Problem (StEP) initiative. Yet it illustrates the multitude of challenges in working out the necessary solutions that require a global multi-stakeholder approach based on science.

Since the United Nations Conference on Environment and Development in Rio de Janeiro in 1992 sustainability has become a widely used term, often used as a catch-phrase for green-washing. The production, consumption and final disposal habits of today's societies, especially in the so-called post-industrialized world, are far from sustainable. Many analysts argue that they have worsened over the past 20 years, also due to ever-growing transnationalization. Unsurprisingly, the calls for progress towards real multidisciplinary non-additive but integrative approaches taking into account the ecological, economic and social dimensions are increasing.

It is without question that the e-waste mountain is one of the fastest growing, posing many layers of challenge on today's societies, especially due to the transnational nature of the supply chain of electrical and electronic goods and its reserve at the end of life of products. The production of TVs, computers, smart-phones, refrigerators and energy-saving bulbs demands the use of increasingly scarce resources. These products also contain hazardous elements. They are often inappropriate disposed of through the normal household bin or by shipment of non-reusable equipment for reuse to developing countries trying to close the digital divide increase the magnitude of the problem. Besides, we should not forget that we still have not channelled problems associated with other waste streams of less complex products to sustainable levels; neither in the post-industrialized world nor the industrializing world. Plastic waste is one prominent example.

But, given that e-waste is a relatively new challenge it also offers new opportunities to develop approaches towards a sustainable solution. And what could be more suitable then developing such approaches under the joint umbrella of the United Nation's research arm, the United Nations University (UNU), committed to assisting humanity to address its pressing problems and the StEP initiative, committed to taking every step towards achieving this vision in a multi-stakeholder approach?

Hence, UNU's Institute for Sustainability and Peace (UNU-ISP) through its operating unit SCYCLE developed a plan to establish a continuous e-waste summer school series in 2008 to become the foremost forum available to young scientists involved in e-waste related research to share their knowledge, interact with experts and develop collaborative partnerships fostering high quality, cutting edge scientific research on all areas related to e-waste; from policy to technology and from economics to social aspects. It was also intended to develop a diverse curriculum in an innovative framework supported by various teaching and learning methodologies and by this support progress towards solutions of the e-waste problem, which could be replicated in other areas.

The e-waste summer school concept was developed to offer young scientists at an early stage of their career the possibility of growing their international networks and multidisciplinary cooperation, which is often only available to senior scholars. But the innovative and partly provocative thinking of those of the second or third academic tier could provide a substantial impetus for the necessary progress towards sustainable solutions.

We are grateful that our vision for this summer school was shared by the Dutch compliance scheme NVMP, becoming the main sponsor of the 2009 and 2010 summer school events. Philips and Umicore also deserve special thanks for hosting the summer schools, the Swiss EMPA in developing the curriculum and guiding the group work through Rolf Widmer and the many experts and lecturers contributing through their expertise to the success of the summer school.

My team members Deepali Sinha Khetriwal, project manager, very ably supported by Claudia Luepschen and Wesley Crock, have done their utmost to making the E-waste summer school a success story, which we hope to continue into the future.

Ruediger Kuehr
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Executive Secretary, StEP Initiative

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Introduction

Deepali Sinha Khetriwal and Claudia Luepschen

Sustainable production and consumption is one of the key challenges of a growing and aspirational global society. To move towards a sustainable future, it is vital that the production, consumption and final disposal of the products we use in our everyday life not only use fewer resources more efficiently while minimizing the use of toxic materials and emissions of waste and pollutants at the same time, but also take place in closed material loops. This requires a shift in thinking as well as societal and technological innovations, appropriate policies, public and private investments, new business practices and multi-stakeholder cooperation.

Electrical and electronic products – from mobile phones to music players to televisions and computers – are some of the most widely available and desired products globally. Ever since the introduction of electrical and electronic consumer durables in the early twentieth century there has been an accumulation of large quantities of these products in society, with rapid technological progress accelerating product obsolescence. While the advantages of these products are evident and are manifest in our everyday life, there is a growing recognition of their adverse environmental impact, given their mass production and intensive use of increasingly scarce resources as well as given their partly hazardous content.

Waste electrical and electronic equipment (WEEE), also commonly known as e-waste, is no longer only a problem limited to rich industrialized countries. The rapid adoption of technological equipment in all parts of the world is resulting in growing quantities of e-waste being generated globally. In addition, many developing countries are dumping grounds for

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e-waste as a result of their importation of products categorized for reuse, though not in fact reusable, and substantially increase their domestically generated e-waste as well.

E-waste has several dimensions, many of which are interlinked. It has an environmental dimension, as it is a waste stream with toxic contents that are hazardous to human health and the environment. In addition, the production of this equipment consumes substantial resources. It has an economic aspect in that it is a rich mine of precious metals, rare earths and other scare minerals, the concentration of which in e-waste is far greater than in any naturally occurring mineral ore. It also has socio-economic aspects, such as who should pay for what, how much and when, as well as the techno-commercial aspects of developing recycling and recovery technologies. Policy and legislation also play a critical role, not only at the local or national level but also at regional and international levels. And lastly, it has a social dimension, as it is the consumers who in the end have to follow the rules set by various compliance schemes and who have to return end-of-life (EoL) equipment.

E-waste management is inherently interdisciplinary in nature. Policies to promote the safe and environmentally sound disposal of e-waste are intertwined with the need for processing technology, infrastructure for the collection of e-waste, financing mechanisms and economic incentives, control and monitoring to ensure compliance as well as consumer awareness and behaviour change.

It seems only natural that e-waste research should thus also be interdisciplinary and several authors in this edited volume have stressed the importance of looking at e-waste through an interdisciplinary perspective. However, given the obvious benefits and, indeed necessity, of collaborative research straddling various research disciplines, there is a surprisingly little, if any, research looking at e-waste in a holistic, multidisciplinary manner. Most researchers tend to focus only on a particular aspect of the e-waste problem, looking at it through their own disciplinary lens. Despite the burgeoning literature on e-waste it is as yet a relatively new research area albeit a dynamic one. Therefore there are many open questions that are still to be answered, while new ones keep coming up with the growing volume of e-waste worldwide, new technical developments and the rapid replacement of old products with new and different ones. While there is still debate on how to best and most efficiently manage existing products, new product categories are emerging; such as electric cars or smart textiles which are currently not considered as e-waste, but which will soon need to be included in the e-waste debate.

While there is debate on whether hydrometallurgical or pyrometallurgical processes are more efficient in the recovery of metals from e-waste, bioleaching technologies are being developed that can also be applied to e-waste. Then there are also the geographical gaps in e-waste research. Most e-waste research thus far has been done in Europe, looking at European systems, problems and solutions, and in Japan. It is only in recently that e-waste research has examined problems and solutions to e-waste in other regions of the world. However, there is a vast area open to future research on e-waste focusing not only on developed countries but also on the different and unique challenges and opportunities created by e-waste in developing countries. E-waste is also coming more and more into discussions on critical materials such as scarce metals and rare earths, especially as a potential source of these precious or hard to find materials which are essential in the manufacture of not only electronics but also in a host of other applications. This book is a first attempt to address part of these research challenges, although more are certain to emerge in the future.

The StEP E-waste summer school – a holistic approach to e-waste research

One of the founding principles of the Solving the E-waste Problem (StEP) initiative is to understand the many dimensions of the e-waste problem and look at it holistically. When the StEP e-waste summer school series was initiated as a forum for young e-waste researchers, one of the main objectives was to facilitate and promote interdisciplinary research. This holistic approach is manifested throughout the programme. The themes of the summer schools aim at creating a red thread through the summer school, linking the various topics and lectures to the overall bigger picture while also reflecting a broad, interdisciplinary focus on e-waste.

In the first year the theme was the product life cycle. The product life cycle starts with the extraction of raw materials, going into production, sale and use (and potentially a second or third use) and then, after disposal and dismantling of the product, coming back into the production cycle through the recovery of the raw materials, ideally substituting the extraction of virgin raw materials. Underpinning each of these stages is policy and legislation, which can impact on each stage. For example, taxes on extraction can influence the input prices of primary raw materials and encourage the use of secondary raw materials. At the design and production stage policies can dictate what materials may be included and which are banned. Policies to encourage the proper disposal and collection of the WEEE and to promote the development of dismantling and recycling infrastructure can all play a role in ensuring that the raw materials are not lost at the EoL of a product or sent to developing countries for illegal disposal, or treated in an environmentally unsound manner. Looking at the each stage of the product life cycle, it is possible to identify not only policy and regulation-related research areas but also their links with social, economic and technological aspects as well. Through the research presented in this volume we hope to showcase a few of these links.

The theme of the second summer school was “Enabling Closed EEE Cycles”, exploring the various enablers of a sound, closed-loop e-waste management system. We identified six main categories of enablers, namely, legislation, finance, logistics, civil society, technology and control and monitoring. Each of these enablers interacts with all the others and plays a critical role in the development of a sustainable e-waste management system that ensures that products at their end of life are returned as secondary raw materials that can go back into the production chain.

Legislation is considered an essential component of any e-waste management system, especially to provide a level playing field for all actors, as well as to set out benchmarks and guidelines. Although there are examples of take-back systems starting as voluntary industry initiatives, there is evidence that in the absence of robust legislation, the systems remain limited in their coverage, for example, of product categories or brands, and costs are externalized in order to retain competitiveness in the absence of a level playing field for all similar product manufacturers. There is a cost to the collection, recycling, recovery and safe disposal of e-waste. While some of the cost incurred can be paid for by the user of the end product, in some cases the inherent value of the material is often not sufficient to pay for either a part of the process or the whole process. The unpleasant consequence of insufficient economic incentives can result in cherry picking, where only economically lucrative e-waste is collected and treated for recovery, while the rest – “the uneconomical” e-waste – is sent for disposal, often without proper treatment.

Logistics is interlinked with the other enablers, such as financing, as well as legislation that dictates, often to a large extent, the nature of the system design. A convenient and efficient logistic system encourages the collection of EoL equipment, reduces the cost of its collection and transportation and provides recyclers with more assurance about their supply, thereby also creating a virtuous cycle of further investment and recycling and recovery operations. Moreover, improved transport and logistics are extremely important to strengthen the reuse of equipment, where logistics currently is still a major stumbling block.

Civil society plays a crucial and continued role in starting and sustainably managing any e-waste management system, as it provides the impetus, vigilance and necessary engagement in the generation of consumer awareness and behaviour change. Civil society institutions such as non-governmental organizations and the media have been in the forefront in bringing the problems associated with e-waste to the fore, and helped press the other stakeholders into action. In addition, eventually, it is the consumers who are key drivers in handing in equipment and improving collection. Technology is often associated with information technology (IT) and products such as computers and mobile phones. However, this is only a very narrow understanding of technology, especially in the context of managing EoL technological products. A broader understanding of technology encompasses the processing technologies for recycling and recovering materials from e-waste, or the application of IT to track, trace and improve e-waste management systems. What is more, technologies are not only technical installations but also skills, processes and combinations of both. There are interlinkages between technology and the other enablers – whether in the application of IT for controlling and monitoring a system, in the development of new processes to recover precious and rare elements from e-waste or used for making logistics more efficient.

All systems need checks and balances, and effective control and monitoring facilitates continued trust in the system to prevent it from collapsing due to free riding or cherry-picking. Control mechanisms at multiple levels are necessary, such as monitoring not both financial and material flows, as well as technical controls to monitor externalities such as emissions and health hazards. Such controls and monitoring must also be applied at an international level, especially in the case of the transboundary movements of WEEE, which in many instances are illegal.

Figure I.1 illustrates how the product life cycle and the six enablers of closed material loops cover the entire spectrum of e-waste research from all academic disciplines. It also provides a visual representation of the various aspects of sound e-waste management, thereby also showing the need for interdisciplinary research. The chapters presented in the following chapters touch upon many of these topics.

Structure of the book

This edited volume provides a forum for young scholars to present their research and contribute to the international debate of challenges and solutions for a global e-waste management. The book contains research that was presented at the NVMP-StEP E-waste Summer School Series 2009/2010. It is structured in five parts.

The first part contains the chapter by Mary Lawhon and Djahane Salehabadi and is aimed towards explicitly considering e-waste in ways that build on social studies of waste, including the recognition of its

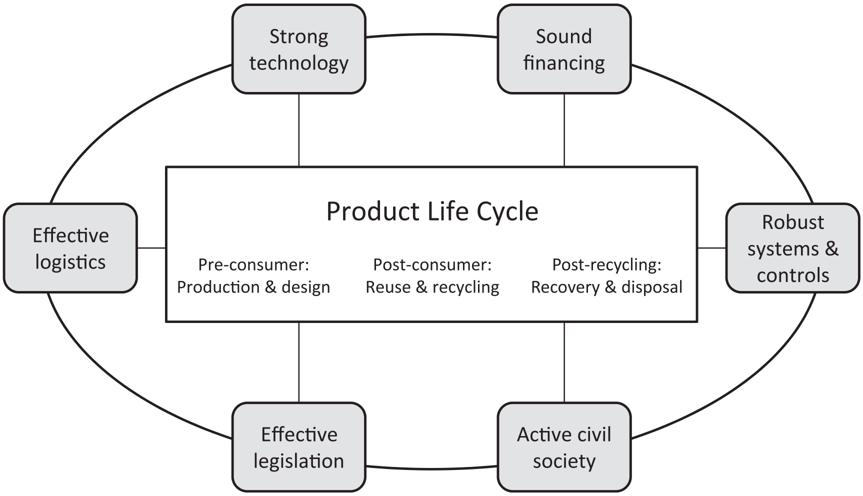

Figure I.1 A holistic look at the e-waste problem

co-constituted material properties and social construction. The authors outline social scientific research on social and material constructions and show how this way of thinking offers critical insights into the e-waste problem.

The second part has two chapters that focus on the concept of environmental justice, which, as the United States Environmental Protection Agency defines it, is the fair treatment and meaningful involvement of all people regardless of race, colour, national origin or income in the development, implementation and enforcement of environmental laws, regulations and policies. Hiromi Inagaki analyses the distribution and structure of economic benefits and environmental health risks of e-waste recycling on a global and national level, drawing on a case study on computer waste flows to and from India. Somjita Laha highlights the way in which capitalism escapes environmental regulations through the informalization of environmentally unsound activities, exemplified in the case of e-waste. The availability of cheap labour and the absence of rigid environmental and health regulations – or the absence of implementing or compliance mechanisms – provide an incentive for exporting e-waste to developing countries, where again, the waste is processed in the informal sector. Both chapters comment on the disproportionate weight of environmental problems borne by marginalized people in the informal sector, constituting a gross violation of the principles of global environmental justice.

In the third part the authors discuss the environmental and health consequences of informal e-waste recycling and the resulting need for more environmental education, based on experiences in Nigeria and Kenya. Innocent Nnorom and Oladele Osibanjo present the results of a study of a site used for the open burning of selected WEEE components to recover the copper, aluminium and other valuable materials in Aba, South-eastern Nigeria. The results indicate there is severe heavy metal contamination of the soil. Further, the metal pollution at the site studied also has the potential to contaminate surface waters through rainwater leaching, of groundwater as well as crops in nearby farms, with obvious health hazards for the surrounding population. Kehinde Olubanjo and colleagues analyse the concentration of lead and copper in different parts of waste personal computers imported into Nigeria. The disposal of e-waste, particularly computers, in Nigeria has become a serious problem since the methods of disposal are very rudimentary and pose grave environmental and health hazards. The situation is worsened as there is no e-waste management system in place, as well as the lack of awareness, inadequate legislative mechanisms, a lack of funds and reluctance on the part of the government and corporate organizations to address this critical issue. The authors call for more environmental education and continuous and detailed education programmes to be implemented at all levels of society.

The issue of consumer behaviour and disposal attitudes is central to the chapter by Elizabeth Muoria and colleagues, who have researched how residents in a municipality in Kenya dispose of e-waste, together with the factors that affect their behaviour and their level of awareness of the effects of poor disposal of e-waste on human health and the environment. Muoria and colleagues' study shows that once equipment is out of use, most of it is either stored or disposed of with other solid waste, either due to its intrinsic resource value or because it is convenient or cheap to do so. Most residents are not yet sufficiently aware of the dangers for the environment and in particular for human health resulting from an inappropriate disposal of e-waste. All three chapters not only shed light on e-waste in the African context but also emphasize the need for integrated e-waste management that addresses the social, technical and legislative challenges associated with e-waste.

The next part of the book deals with system design approaches for sustainable e-waste management systems, given limited resources and limited carrying capacity of our ecosystem. Henning Wilts explores how the circulation of palladium, a scarce metal found in WEEE, can be improved by means of international covenants, negotiated but binding treaties based on private law between public institutions, industry and other stakeholders, for electronic products. A policy approach that is already widely adopted for the sustainable management of e-waste is the concept of extended producer responsibility (EPR), which encourages producers to design environmentally friendly products by holding them responsible for the costs of managing their products at their end of life. The European WEEE Directive, as one of the pioneering legislations on the sustainable management of WEEE, is based on the principles of EPR. Hazel Nash explores the extent to which the WEEE Directive and the WEEE Recast Proposal promote patterns of sustainable consumption and production. In particular, the chapter assesses the ways in which the roles and responsibilities of producers and consumers are addressed and the impact this has on achieving the overarching aim of sustainable waste management. Hua Zhong and Shu Schiller explore the implementation of an EPR strategy in China. In their chapter they proposes a third-party take-back model as an alternative approach where private companies assume the EoL responsibilities for products on behalf of the original equipment manufacturers. They argue that such a third-party recycling system, by means of an internet platform to organize the collection and recycling of WEEE, could balance the interests of all stakeholders involved: the consumer and the third-party recycler contracted by the manufacturers, as well as the government as the regulatory body.

In part five, we look more at the technological challenges and innovations in managing e-waste, in particular bioleaching processes to recover metals. Conventional recycling processes are either hydrometallurgical (meaning the separation of metals by liquid processes, such as leaching) or pyrometallurgical, which entails thermal treatment. However, bioleaching can be an alternative method for recovering metals from WEEE. Metals-bearing waste like EoL vehicles or waste EEE are often recycled using post-shredder techniques encompassing gravimetric, magnetic or eddy current separation stages, which result in large amounts of materials such as plastics, foam or textiles that have to often be dumped in landfills. High dumping costs and recent advances in the hydrometallurgical extraction of metals have increased interest in hydrometallurgical processes and other alternatives. The use of microorganisms to solubilize metals from waste is one such potentially low-cost alternative to the classical hydrometallurgical processes. Bioleaching does not need high temperature and pressurization, which reduces the energy cost and avoids the emission of gas pollutants. Today, bioleaching is applied on a commercial scale for the recovery of copper and uranium from low levels ores and sulphide minerals. However, studies have demonstrated that metals can be recovered from printed circuit board scrap by bacterial leaching. Gregory Lewis and colleagues investigate the potential of bioleaching of polymetallic industrial waste using chemolithotrophic bacteria while Luciana Harue Yamane and colleagues discuss the influence of ferrous iron supplementation on bioleaching to recover copper from printed circuit boards.

Part I

The sociomateriality of e-waste

1

Fixing the e-waste problem: An exploration of the sociomateriality of e-waste

Mary Lawhon and Djahane Salehabadi

Introduction

Concern over the environmental and health impacts of digital technologies such as personal computers, iPods and mobile phones has increased in recent years. Although public and scholarly attention was previously focused on the stages of production and use of these items, it has recently turned towards their end of life. Media articles with titles such as "Your Laptop's Dirty Little Secret" (Walsh 2008) and "E-waste: Dark Side of Digital Age" (Mayfield 2003) suggest that, contrary to predictions that the technological revolution would lead to dematerialized and thus sustainable societies, digital technologies have serious negative health and environmental implications. This is not only because e-waste is the fastest growing of all waste streams but also because discarded digital items contain mercury, cadmium and plastics rich in brominated flame retardant and lead-rich cathode ray tube glass. Thus disposing or recycling them often releases toxic chemicals into the air, water and soil. Given the toxicity and abundance of e-waste, countries across the globe are struggling to find ways to efficiently and responsibly handle discarded electronic goods (see Kahat and Williams 2009; Nnorom and Osibanjo, 2008; Oteng-Ababio, 2010).

Internationally, the exportation of e-waste from the global North to the global South[1] has drawn much attention. Evocative images of smouldering e-wastelands in China, India and West Africa echo those of the toxic waste dumps in the global South during the 1980s (see Clapp 2001).

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These images suggest that, once again, the poor and marginalized and their environment are paying the price for the affluent, high-tech lifestyles in the North. In contrast to the 1980s international law now bans the export of hazardous waste from North to South, yet exceptions can be made to this rule and illegal exports continue. Various angles of this problem have been investigated in technical studies and analyses of environmental injustices, and yet, the way in which waste is understood in many of these studies remains implicit. We seek to demonstrate in this chapter how the e-waste literature can be enhanced by drawing on social studies of waste and its materiality, as well as how our work on e-waste can inform social studies of waste through examination of the instability of sociomateriality.

Work on the materiality of waste seeks to emphasise the agency of things while also acknowledging social construction. In this chapter, we use the term sociomaterial to draw attention to the inseparable co-constitution of the social and material. Our contribution in this chapter to the broader field of social studies of waste is through our focus on the instability of the sociomateriality of e-waste. For, as Corvellec and Hultman (2012, 3) argue, "socio-materiality is not fixed. Instead, the socio-materiality of waste is contingent on the social understanding that people have of the nature, origins, and destiny of waste as material". Building on this work, we begin to articulate more carefully and explicitly the dynamic sociomateriality of waste through the concept of "fixing". Here, we juxtapose two main uses of this term: to repair or put in order, and to hold in place or position. We suggest that, in attempting to fix (repair/order) the e-waste problem, regulation often fixes (stabilizes/holds in place) e-waste. We also explore the implications of fixing, repairing and ordering by fixing, stabilizing and holding in place for political economy and policy.

Specifically, we argue that the regulations that attempt to solve the e-waste problem by banning North to South exports are responding inadequately to the dynamic sociomaterial construction of e-waste. This chapter illustrates that e-waste cannot be fixed simply through regulatory mechanisms, as the category of waste is constructed on the basis of by whom, when, and where it is defined. We focus on the issue of e-waste imports and exports as the most salient controversy on e-waste and contend that in order to understand the flows of e-waste we must move beyond a simple narrative of North–South dumping and recognize how the hybrid sociomaterial construction of e-waste shapes its movement.

Below, we outline social scientific approaches to the study of waste, including its social construction and sociomateriality, and elaborate on the concept of fixing the category of waste. After a brief note on the methods used in this study, we show how these concepts offer critical insights into the e-waste problem by exploring case studies of German and South African e-waste regulation and practice. Germany's e-waste legislation, among the earliest of its type and considered to be both comprehensive and forward thinking, is a useful example of the limitations of regulation for, despite these progressive efforts, illegal exports to the global South still continue. We analyse the tension between domestic legislation, which constructs e-waste as having potential value, and export regulations, which construct it as valueless. The German story is juxtaposed with the case of South Africa. Here, an industry-led initiative is attempting to reshape social practices around e-waste, recognizing both its potential risks and value. We suggest that changes in practice may destabilize established regulations and notions on the importation of e-waste. We then conclude with a broader reflection on the relationship between policy and practice and the ability to fix waste as a category.

Social studies of waste

In this section we review social scientific engagements with waste to show how insights into the sociomateriality of waste can inform debates over global e-waste flows. As Moore (2011, 2012) suggests, defining waste is a complicated task. Rather than adopt a single definition, we draw on Moore's (2012) recent review, which categorizes geographies of waste. We suggest that by attending to the dynamism of the category of waste we may take into account how certain actors, policies and practices attempt to stabilize –to fix – the category of waste in an attempt to fix a particular problem.

Waste as social construction

Cultural approaches to waste demonstrate that the transformation of an object from commodity to waste and from waste to commodity is not given. There is nothing inherent in an object that makes it garbage; racial and gender ideologies, cultural norms and political and economic relationships shape the materiality of technologies (Pinch and Bijker 1984; Scharff 1992). Waste is socially constructed; it is defined as such on the basis of by whom, where and when it is defined. Gille (2010, 1050) adopts a utilitarian perspective by calling waste "any material we have failed to use to to leave open the opportunity to demonstrate the material and social consequences of one type of waste material metamorphosing into another". Evidence of this definition is found in the prevalence of second-hand shops and waste pickers on landfills, and the use of waste in art exemplifies the myriad ways in which uses can be found for unwanted goods (Åkesson 2006). Further, what is waste to humans may not be so to other species.

Additionally, the category of waste is spatially contingent. As Douglas (1966, 41) famously argued,[2] dirt is "matter out of place". Depending on where objects are located, they shift from the class of waste to that of commodity, for there are particular culturally specific spaces where waste should be found or placed (Gille 2007). In the USA a baby seat placed in the driveway or in a garage is recognized as a valued possession but when that very same object is placed on the curb it is seen as waste (Gille 2007). The imposition of one culture's waste spatiality onto another can lead to conflict (Argyrou 1997).

Historians have shown that waste also has a temporal dimension and that items valued in a particular historical period can become waste in another (Melosi 1981; Strasser 1999; Zimring 2005). For example, in the early nineteenth century scrap metal was a valuable resource, but since the introduction of mass production and the consequent need for a homogenous supply of raw materials it has lost its value and became waste. Economic changes mean it is once again regaining value (Strasser 1999; Zimring 2005).

Waste also has a temporal dimension at a much smaller scale, and can be viewed as a moment in the circulation of a material (Gregson et al. 2010). Drawing on and critical of Appadurai's (1986) call to follow the thing, Gregson et al. (2010) note that this call has often resulted in examining stable objects. In contrast, studying waste – in their case, the end of life of ships – "shows that the thing is multiple, mutable and material; and that the thing and the commodity are but moments in the circulation and assembling of material" (Gregson et al. 2010, 848).

Conceptualizing waste as socially constructed helps us see beyond technical and economic debates about waste and into the politico-economic sphere (Gille 2007). The fluidity of the category of waste is important because the act of classification is shaped by and reproduces power relations within society (Thompson 1979). The powerful, however, are not singular, for there are many competing powers, and they are not able to determine unilaterally what is waste, who is allowed to create or extract value from it and what its value is. While definitions may be legislated and socially accepted, they are simultaneously reshaped through practice. For example, waste in landfills is generally viewed as valueless. Nevertheless, informal waste collectors actively resist and reconstruct this meaning. They reimbue it with value through the process of collecting and returning materials to the economy through sale for recycling or reuse (see Gutberlet 2008; Myers 2005). The struggle to determine what is and is not waste is not just an economic struggle. There has long been an association between waste, immorality and the uncleanliness, but new forms of waste morality are arising (Gille 2007; Hawkins 2006). For example, there is a growing morality – a sense of having done the right thing – associated with the practice of recycling (Hawkins 2006). Despite the extensive reshaping of the meaning of waste over time and space, however, the category is not infinitely malleable.

The sociomateriality of waste

The concept of materiality responds to the narrow emphasis of social constructionists. Deconstructing the category of waste has shown the concept's dynamism yet, as Bakker and Bridge (2006, 5) argue more generally, studies following the cultural turn are "yielding diminishing returns". The literature on materiality has responded to the narrow emphasis on social construction to draw our attention back to the material sphere. This literature primarily examines resources and primary products such as oil, diamonds, water and agricultural products (Bakker and Bridge 2006), but the examination of waste clearly suggests the need to widen the scope of materials (see Lawhon 2012b). Below, we apply these ideas to e-waste, showing how this complex, industrially produced resource can further our thinking on materiality.

Studies of materiality insist that the material matters, but this is not the same as claiming that the material determines everything. Instead, taking economic, political, social, cultural and material factors into account provides a powerful tool for analysing social and historical processes (Crosby 1988; Igler 2004; Mitchell, 2002). This enables us to recognize connections between material objects and the social sphere and challenge the conceptual dichotomy between the social and the material.

Bakker and Bridge (2006) provide an extensive overview of the promise of materiality studies, particularly for resource geography. From their literature review they derive two related assumptions that are relevant to the issue of e-waste. The first is that materiality decentres agency. As Mitchell (2002) argues, historians and social scientists tend to assume a priori that the agents of socio-historical change are humans. A focus on materiality challenges this presumption and pushes us to engage with how non-human agents such as microbes or animals, landscapes or technological infrastructure, shape social processes and relationships.[3] The numerous commodity stories geographers have produced in recent years exemplify this argument. For example, Le Billon (2001) shows how the material properties of resources influence their appropriation for war and Bakker (2004) shows that water is an uncooperative commodity that resists privatization.

The second point is that materiality has politico-economic implications. Rather than simply viewing a resource as an object with material implications, various works explicate for whom and how these implications are relevant. Kaup (2008), for example, shows how the materiality of natural gas in Bolivia shapes who is able to develop it and thereby profit from the resource. Because natural gas requires large-scale investment it "appears to have a certain affinity with large-scale capital investment". These material properties therefore constitute "obstacles for some and opportunities for others" (Kaup 2008, 1737).

Strasser (1999) similarly draws attention to the politico-economic implications of the materiality of waste (see also Gregson 2011; Gregson and Crang 2010; O'Brien 1999). She notes that the transformation of any good into a commodity is always also the function of a particular socio-politico-economic moment. Further, its use or lack of use is thus neither inherent nor given, nor is it singularly determined by the material properties of the waste product in question. Strasser's work on the scrap metal industry in New York City recounts how itinerant peddlers collect old or broken metals from households, and through barter and exchange provide this scrap to individual metalworkers. During this period, scrap metal was a valuable commodity as production practices at the time made its transformation into a commodity possible. However, as mass production began to require greater uniformity and volume of materials, a shift occurred away from these small-scale practices with distributed power and towards the demand for raw materials and more centralized control over them. This shift, in turn, disempowered the itinerant peddlers, removing the market for their collected goods and making their socio-economic role redundant (Strasser 1999).

A promising direction in waste studies that draws on theorizations of both the social and material is Gille's notion of the hybridity of waste (Gille 2007, 2010). The concept of hybridity is borrowed from social studies of science (Latour 2005). It draws attention to the ways in which the social and material, as inextricably bound entities, continually shape and reshape each other. Gille builds on environmental sociologists, environmental historians and sociologists of science to argue that cultural approaches to waste overlook an important point: waste has a materiality that shapes how and by whom it is handled (Gille 2007). Citing examples from her work in socialist Hungary, she contends that policymakers and analysts overlook the material composition of waste, resulting in ineffective waste management policies that cause unintended health and environmental damage. The material must not simply be added to the social as a separate entity: instead "we need to pay attention to culture, materiality, and economy all at once" (Gille 2007, 27). Some of these factors will be of greater significance than others under some circumstances, and understanding what and why particular factors matter is critical to research (Gille 2007). Like many of the studies of materiality cited above, Gille extends the literature on materiality by addressing issues of the unevenness and power as well spatial and temporal contingency.

Fixing waste

As the studies above illustrate, waste is a dynamic category. And yet, while research has highlighted this dynamism, these ideas are not always incorporated into the wider literature (see Moore 2012) or into policy and practice. Gille (2007) (see also Gutberlet 2008) shows how socialist Hungary attempted to redefine certain materials as not waste, but as shown below, many e-waste policies attempt to fix certain materials as waste. We suggest that there is much to learn from the processes through which actors, in attempting to fix (repair/order) a problem, seek to fix (stabilize/hold) the category of waste.

Gregson et al. (2010, 853) argue that in order to better understand what they call the transience of waste, we need to more carefully articulate the sites, practices and actors involved in the translation, transformation and revaluation of waste. They suggest that transience is spatial: "To work with the future potentialities in things, with what things might become, is not an art possessed equally by all places". It is also based on categories and markets:

> Animating materials anew, rekindling them is curtailed not just by limits of the imagination, by knowledge or indeed by ways of seeing, it is framed too by the categories and classifications that surround stuff in particular parts of the world – particularly discarded objects declared to be 'end-of-life' – and by the markets that are available to goods fabricated from secondary materials.

Transience may also be most possible in the global South, for "the places in the world where the arts of transience are most vividly articulated are precisely those places where materials and 'wastes' are lightly regulated or unregulated and those where end-of-life goods inexorably find their way to as a result" (Gregson et al. 2010, 853).

We agree with Gregson et al. (2010) that there is merit in examining the transience of waste as well as the means through which actors intentionally or unintentionally fix (stabilize/hold) or unfix (destabilize) this category. In our study we demonstrate the political and theoretical significance of examining efforts to fix (repair/order) e-waste flows. We use these apparent efforts to fix (repair/order) the category of waste as a platform from which to explore how the category of waste becomes unfixed (destabilized).

Framing e-waste

In this section we apply the notion of the hybridity of waste specifically to e-waste. We first review key themes in the e-waste literature. This review is not intended to be exhaustive but to show the particular social or material framings on which certain studies draw. We suggest, following Moore (2012), that environmental justice and technical studies of waste, as well as e-waste policies, tend to represent the category of waste positively – as being defined by particular categories. These properties of waste are, we suggest, largely seen as fixed, static and given. Such works focus almost exclusively on waste's material properties (its value and toxicity, separately by Moore into two separate domains although in the literature sometimes both are given attention) without adequately attending to the sociomaterial construction of these properties.

Categorizing the e-waste literature

Lepawsky and Billah (2011) categorize the e-waste literature in three different strands: environmental justice, environmental toxicology and waste management engineering. They suggest that these strands share "an underlying assumption that the only possible outcome of the production–consumption–disposal chain is some form of waste, be it effluent, emissions, or toxic hazard" (Lepawsky and Billah 2011, 212). These studies fix (stabilize/hold) e-waste as hazard, in line with the positive, dualist frame described in Moore (2012). The environmental justice literature in particular uses evocative images of danger and desperation. News articles, non-governmental organization (NGO) reports and some scholarly works generally make three key points: e-waste is the world's fastest growing waste stream; e-waste is toxic; e-waste gets exported from wealthy northern countries to poor places that lack the technical, political and economic capacity to safely handle and dispose of these items (see Nnorom and Osibanjo 2008; Pellow 2007; Puckett et al. 2002). Echoing debates over the export of toxic waste during the 1980s and drawing on environmental justice rhetoric, this narrative – written by and to the dumpers – claims that "we" dump the ecological and social costs of our affluent, high-tech lifestyles on the most vulnerable parts of the globe.

While the environmental justice literature draws policy recommendations based on the principle of justice, much of the waste management engineering research draws policy recommendations based on an assumed particular materiality. According to this logic, because e-waste is made of substances such as plastic, glass and metal, and contains particular chemicals, it must be handled in a particular way. Such approaches can be seen, for example, in the collection *Computers and the Environment*

(Kuehr and Williams 2003) in which the social is treated as if it is predictable and stable, and is free of power relations (Lawhon et al. 2010). This work is similar to those reviewed in Moore (2012) in the categories of "waste as (non-Marxist) commodity" and "waste as manageable object" (Moore 2012), which suggest that value of e-waste is enough reason to allow it to flow or which focus on e-waste as a topic for management.

Lepawsky and Billah (2011, 213) add to their initial classification of the literature that the "conceptualization of cast-off electronics as being inherently about waste has begun to be questioned", citing Kahhat and Williams (2009) and Lepawsky and McNabb (2009). In addition to these efforts to identify existing value in waste, there is a growing network that seeks to reframe e-waste as value. This network is composed largely of industry representatives and the Solving the E-waste Problem Initiative – an international organization that includes influential consultant researchers from the Swiss Federal Laboratories for Materials Testing and Research, seeking to solve the e-waste problem. Members of the network argue that "the enormous resource impact of electrical and electronic equipment ... is widely overlooked" (Schluep et al. 2009, 6) as e-waste is a resource-rich ore containing valuable metals such as copper, gold, platinum, coltan and indium. They suggest e-waste can be used to create jobs and contribute to bridging the digital divide.

Many of these authors are seeking to perform research in order to redress a problem with e-waste. However, it is not clear precisely what problem they are seeking to fix. As Lawhon et al. (2010) show, different research questions define the e-waste problem in different ways and provide various means through which to fix the problem including economic, political and technological solutions.

E-waste as sociomaterial construction

In place of accounts that underemphasize the social or the material, in this section we seek to provide a sociomaterial account similar to that in Moore's (2012, 11) fourth quadrant, in which waste is conceptualized as "a constitutive element in contemporary sociospatial relations and economic processes" and in which waste is viewed as "the (often) unvalued and indefinable." E-waste is constructed of various components, each of which has a different precedent and potential for management as waste. If we consider the components separately – as glass, plastic or metal, or even hazardous components like cathode ray tubes – then e-waste produces hardly any practical or theoretical challenge. Yet we cannot consider these components in isolation; as Gregson et al. (2010, 848) note, the "thing is multiple, mutable and material". What challenges us in the case of e-waste emerges from the need to consider these components together, and the consequent need for the separation and management of the different components.

This material complexity results in a situation in which efficient separation is critical to obtaining maximum value. Efficient separation has generally been found to be best obtained by dismantling and separating the waste manually, given the non-uniformity and integration of materials. If done correctly, manual separation is more efficient and poses little, if any, environmental risk (Schluep et al. 2009, Williams 2005). Thus the sociomateriality discussed above has consequences not just for whether goods can be made into new goods, but for who may profit from doing so. Unlike the conclusions drawn by Kaup (2008) that natural gas favours large-scale capital investment, labour-intensive manual dismantling is preferable for some parts of the e-waste recycling process. This preference for manual dismantling and separation has led to extensive recycling in the global South.

Findings are also emerging that high-tech facilities with integrated smelters (of which there are currently five in the world) are better able to extract precious metals from e-waste. Therefore, it has been argued that the most efficient recycling combines manual dismantling and separation with high-tech smelting. A prime example of this is the "Best of 2 Worlds" project in which the manual labour is performed in China and then certain components are taken to the global North where high-tech northern multinationals recover the precious metals (Wang *et al.* 2012). A closer analysis suggests that this pattern of manual separation in the global South and high-tech processing in the global North results in low profit processing taking place in the global South, while high profit processes occur in the global North. The conclusion that high value processing is best done in the North with high-tech facilities – reached by a researcher from Umicore, a European e-waste refiner – is, however, not uncontested. Some question whether this practice is truly more advantageous, and whether it might not be better to upgrade facilities in the global South to keep resources local and enhance economic opportunities in these regions.

The question of how e-waste will be processed draws our attention to the fact that the notion that e-waste is hazardous is not given. This is not only because discarded electronic goods can be redefined as valuable commodities but also because whether e-waste is hazardous or not depends on what happens to it. The simple re-use of materials is not hazardous and although there are hazardous components inside the discarded materials, these are contained. Many aspects of manual separation are not hazardous. Cables themselves are not hazardous, but the process of burning them to access materials calls forth the framing of e-waste recycling as hazardous. This suggests that the very definition of what is toxic waste is contingent on how the waste will be processed.

Methods

Understanding e-waste as a hybrid helps us see that the politico-economic implications of sociomateriality are not given but are socio-historical outcomes. The current e-waste political economy is shaped by broader patterns but it is also undergoing dynamic change. In order to better understand this change and assess the impact of various regulatory efforts, we examine e-waste policy and practice in Germany and South Africa. Germany provides a useful example of some of the earliest and most stringent e-waste export regulation, while South Africa is currently attempting to establish formal regulation. The countries' different politico-economic contexts, particularly in terms of waste, also provide useful contrasts. The authors' familiarity with these countries also motivates their comparison. Fieldwork in both countries was conducted in 2009 and early 2010, including over 60 semi-structured informal interviews with government officials, formal e-waste recyclers, informal recyclers and environmental NGOs. The interviews were supplemented by an analysis of media and policy documents as well as by non-participant observation of meetings and industries in both Germany and South Africa. In the following section we describe how actors are seeking to reorganize the flow of e-waste and its associated value and risks. We demonstrate the value of using the lens of sociomateriality, some problems that attempts to fix (repair/order) waste generate, the challenges of fixing (stabilizing/holding) the category of waste and the need to consider the consequences of efforts to fix (repair/order and stabilize/hold) and unfix the category of e-waste for policymakers and practice.

Fixing e-waste through regulation

In this section we use the lens of sociomateriality to analyse recent e-waste regulations in Germany and South Africa. Using the example of Germany, we demonstrate how regulations consider the category of waste as fixed (stable/held) and therefore fail to fix (repair/order) the problems they are intended to resolve. South Africa's attempts at regulation more clearly respond to both the potential value and risks of e-waste's materiality. However, it is possible that that fixing (repairing/ordering) by establishing a new sociomaterial regulatory system may in turn unfix (destabilize) the established discourse on e-waste imports. The new context of practice may thus shift the e-waste discourse and consequent e-waste policy.

Germany

A focus on e-waste in Germany calls to our attention the need to consider sociomateriality when deriving policy and the politico-economic implications of e-waste's hybridity. The German government has passed two important e-waste regulations: the Electrical and Electronic Equipment Act (ElektroG) in 2005 and the Waste Shipment Act (AbfVerbrG) in 2007. Underlying these laws are contrasting framings of the supposed nature of e-waste. This results in a tension in the two laws and facilitates the emergence of an e-waste system that favours large capital enterprises and squeezes out the informal e-waste sector.

Germany's AbfVerbrG is the latest national transposition of the Basel Convention and bans the export of hazardous waste, including e-waste, to the global South. The problem is defined as the dumping of undesirable waste and its solution as stopping these exports. In order to do so, this regulation attempts to fix (stabilize/hold) post-consumer electrical and electronic goods as e-waste – as unwanted, undesirable material. The premise underlying the AbfVerbrG is not to deny people in the global South access to a resource but that toxic waste has no value and its export must be outlawed to protect the poor. However, the law is unable take into account the dynamism of the notion of e-waste and it fails to engage with the complexity of e-waste's materiality. Thus it is relatively ineffective in governing e-waste flows out of Germany. We suggest that, despite the imposition of this terminology and efforts to obscure waste's dynamism and potential desirability, actors have challenged the categorization of post-consumer electrical and electronic goods as waste. Further, e-waste's complex sociomateriality and the inability to fix (stabilize/hold) the notion of waste in practice (despite fixing it in policy) have contributed to the ineffectiveness of this legislation. This is because informal actors in Germany see the value in discarded electronic goods: as reusable goods, spare parts and precious metal ores. These informal actors, who are mostly immigrants from Eastern Europe, Africa and the Middle East, gather discarded items by going door to door, standing outside waste depots, buying it through eBay, craigslist and other online second-hand markets and by purchasing items in bulk from schools, businesses and government offices.

The enforcement of this regulation is hampered by the complex sociomateriality and dynamism of the category e-waste. It is difficult to determine by a visual inspection whether the equipment is functional, making labelling and monitoring of these exports difficult even when the political will is there. Moreover, it costs more to export used electronic goods from Germany than to recycle them domestically. This challenges media and NGO assertions that local recycling companies export discarded electronic goods to pay the cost of state-mandated domestic recycling. Instead, e-waste flows out of Germany because it has a desired value – as reusable goods, spare parts, metal ore and raw materials.

In practical terms, not only are the existing laws unable to keep e-waste in Germany, but the reification of e-waste as toxic also has the potential to disenfranchise the informal sector. Instead, it privileges capital-intensive, high-tech e-waste processing firms in the North who claim to be able to process e-waste in a more efficient and environmentally responsible manner. However, electronic goods do not have to be designed in such a way that the informal sector cannot recycle them safely, and as discussed above, the current sociomateriality of these goods means that greater recovery rates can be obtained by using manual methods. However, despite attempts at designing out the toxic elements and extensive lobbying by organizations such as Greenpeace and the Basel Action Network to reduce these products' environmental impacts in this way, there is little discussion of how digital electronic goods can be redesigned specifically so as to enable manual (and often consequently informal) dismantling. Germany's e-waste laws therefore facilitate the creation of a waste system in which certain actors are able to create wealth out of waste and others are squeezed out, and options that would challenge existing power relations remain unarticulated, let alone explored.

The second major regulation that Germany has adopted takes a different approach to e-waste. While the AbfVerbrG seeks to define a sociomaterial product as waste, ElektroG tries to define – for particular actors – an unwanted sociomaterial product as non-waste. ElektroG is underpinned by the principle of extended producer responsibility (EPR). This principle seeks to apply the idea that waste is a dynamic social construction and to reframe waste as a resource and encourage domestic recycling. It includes an explicit engagement with the uneven politico-economic context in which the transformation of waste into a commodity occurs. However, since their introduction EPR policies have been critiqued for being ineffective in accomplishing their stated goals (such as stimulating design for the environment) (Sachs 2006; Walls 2006). As manufacturers no longer produce the equipment they place on the market and they prefer to contract out disposal than actually handle waste themselves, they have little incentive to revalue their discarded goods and redesign their products with waste minimization in mind.

While the intended target of Germany's domestic e-waste law, the manufacturers themselves, have yet to see any value in waste, the growing market value of precious metals has led formal and informal entrepreneurs to create value out of discarded electronic equipment. Since one of the primary underlying objectives of Germany's waste management – and particularly the ElekrtroG – is the reconceptualization of waste as valuable one might expect a strong reuse and recycling sector to please policymakers and environmental NGOs. Indeed, certain e-waste recyclers – namely formal, large-scale recycling firms – are supported and praised for the important work that they do. However, despite the pressure for a shift in concepts and practice from waste to recyclate (raw material to be sent to be recycled), Germany's informal e-waste sector has been the target of much public criticism because they export the materials they collect. These examples show that German policy has been unable to fix (stabilize/hold) the category of waste through policy-making in order to fix (repair/order) the problem of e-waste exports. Similarly, German policy has also been unable to fix (repair/order) the problem of exporting waste by unfixing (destabilizing) the established way the manufacturers view waste. Manufacturers' views of waste have remained fixed (stable/held).

South Africa

As at early 2011 no legislation specifically targeting e-waste has been promulgated in South Africa (see Dittke 2007 for a review of the relevant legislation). Instead of analysing policies, here we identify current concepts of waste and waste policy that are relevant to future regulation as well as the types of regulation being sought by an industry-led initiative, the e-Waste Association of South Africa (eWASA). This association is attempting to change domestic e-waste practices through voluntary initiatives that will then shape government policy.

Improper waste management is prominently discussed as a problem in South Africa, as evident in the 2008 National Environmental Management: Waste Act. The introduction to this legislation identifies concerns about protecting people and the environment from the impact of waste, but also requires consideration of the waste hierarchy (in short: reduce, reuse, recycle). Waste conflicts, concern more than just matter out of place in South Africa. As in many places, getting waste to the right places is insufficient to control it, as contestation exists over where – and near to whom – the right places are and how landfills should be managed (Peek 2002; Lawhon, 2012a). Contrary to these negative portrayals of waste, there are also efforts by government and civil society at various levels to draw attention to the potential value of waste. For example, the national Department of Trade and Industry (DTI 2009) recently published a report examining the business potential of various recycling industries. Environmental NGOs are also working for the contribution of informal waste recyclers in reducing waste quantities by reclaiming materials from landfills to be recognized (Samson, 2008). These efforts are reshaping discourse around waste.

The regulatory context of e-waste in South Africa is similarly undergoing changes because of the recognition of the value and risks associated with processing e-waste. eWASA was established to coordinate voluntary standards, knowledge-sharing and improved environmental management at the end-of-life of electronic goods. It was set up with the help of Swiss expertise and funding (Widmer et al. 2005; Lawhon 2012c). eWASA has now split into two organizations, eWASA and the ITA Information Technology Association of South Africa Producer Environmental Group (ITA PEG) but the aim of improving e-waste management through collaboration between manufacturers, recyclers and government remains the same for both. The two reasons most cited by respondents for these initiatives are to prevent the problematic informal processes that are occurring in other parts of Africa (and eliminate those allegedly occurring already on a small scale in South Africa) and to exploit the possibility of extracting value from the e-waste.

Recently proposed legislation, which is still in draft, may require the establishment of government-approved industry waste management plans to better manage e-waste. The two organizations can be seen to be competing for the legitimacy to develop and obtain support from industry for their plans, and at the time of writing are expected to voluntarily submit plans to government for approval. According to the chairman of eWASA, the association is "working on incorporating the international standards as found under the European Waste Electrical and Electronic Equipment Directive (WEEE) in the proposed Waste Management Plan" (Keith Anderson, quoted in Kruger 2012). The ITA PEG plan (2012) similarly provides for the possibility of applying global standards, although the existing draft of the plan leaves the definition of standards up to the E-Waste Registry, a body to established after the plan is approved.

While these changes are generally viewed as positive steps towards better environmental management, they must be considered within the broad politico-economic context. All the local stakeholders who were interviewed for this research were opposed to the importation of e-waste from the global North, a position that is in line with South Africa's commitments to the Basel Convention (although there is scope for specific imports, there is reportedly no political will to make exceptions for special cases). However, this position was not based on the objectively defined desirability or undesirability of waste, as all our respondents supported the idea of importing e-waste from other countries in the region. From this, we see that the value of e-waste is not given, but based on its location: e-waste from other, poorer countries is acceptable, while the materially identical e-waste from richer countries is unacceptable. This observation suggests that the origin of the waste outweighs other considerations, enrolling the question of justice into the definition of waste.

While this position regarding the import of e-waste is fairly universal, some respondents suggested that changes in e-waste management practice would unfix (destabilize) the category of unacceptable waste. As discussed above, whether e-waste is hazardous or not is in part dependent on whether and how it is processed. Changing the way in which its components are managed to meet higher standards will result in a reworking of the interpretation of e-waste. Should eWASA and or the ITA PEG successfully coordinate changes to practice, the rationale for the Basel Convention that "global waste management policies must be designed against the backdrop that developing countries have limited capabilities to manage wastes" (Okereke 2006, 730) may no longer hold.

A small but notable minority of interviewees suggested that if e-waste management were to meet improved, European or global standards and create local employment, then e-waste imports from the global North should be legalized and encouraged. For these interviewees, the waste is not constructed as unwanted if its management can profitably meet certain standards. Thus, changes to South Africa's capacity to manage e-waste changes will unfix (destabilize) the established position on categories of unacceptable e-waste imports. This changed perspective towards e-waste import, it must be noted, is not an explicit part of either organizations' objectives, and we consider this shift to be at least in part unintended (although possibly, at least for some participants, this is an intentional but unarticulated goal). Thus, while respondents' views on whether e-waste should be imported is framed as a fixed perspective, reflection on future changes to its management suggest that this perspective is actually conditional.

New sociomaterial practices will also have politico-economic consequences. A range of processing methods occurs in South Africa, including manual dismantling and local smelting to extract metals and export them to Europe. At the time of writing the recycling industry consists primarily of small to medium labour-intensive regional recyclers who engage directly with owners of e-waste, such as businesses and government (Finlay and Lietchi 2008). As discussed above in the case of Germany, informal practices are cited as an important reason for regulating this activity, but in South Africa harmful practices have been reported among both formal and informal recyclers (Finlay and Lietchi 2008).

Although the e-waste context currently favours small, regional industries, the eWASA and ITA PEG plans are likely to change the type of benefits and practices of e-waste processing. eWASA is seeking to centralize the collection of e-waste into formal businesses to increase its efficiency, shifting opportunities away from smaller or informal waste collectors (although some low-level engagement with these actors may continue). While some interviewees noted the absence of informal waste collectors at eWASA meetings, there has been no specific effort to encourage or enable their participation or specifically articulate how they may be impacted on or included in proposed new practices. Concerted efforts are being made to assist formal businesses to develop the capacity to improve their environmental practice, but no parallel efforts are being made for the informal sector. Centralization and increased bureaucracy may also favour large industries, as it has been reported that the membership fees and auditing costs are uniform regardless of the size of the company, and tenders for e-waste processing appear likely to be given to a small number of large businesses. The different patterns for formal and informal businesses may be symbolized in the membership of eWASA. Concerted efforts have been made to include the major players in South Africa and the advisory board is made up of international industries. While this does not guarantee policies that are favourable to these entities, we note the possibility as a potential concern. ITA PEG has been in existence for a much shorter amount of time that eWASA, but is similarly controlled by manufacturers. Their plan suggests opening out clearer avenues for the incorporation of smaller enterprises and for competition between businesses to possibly enhance opportunities to access e-waste. However, the overall impact that such formalization will have on the e-waste industry, the environment, and the broader economy remains both unclear and underexplored.

What is clear from the suggested changes to practice is that collaborations between manufacturers, recyclers and the government are seeking to redefine e-waste as a resource. This is in line with existing practices that largely seek to extract value from e-waste, but this initiative seeks to prescribe careful and environmentally responsible practices. This approach accords with progressive views of waste in the Waste Act and with the DTI's efforts to create an economic opportunity out of waste. What impact such a redefinition of waste will have on international e-waste trade policy, however, remains unclear. While some respondents consider that e-waste imports from the global North are undesirable, others note that changes in practice may unfix (destabilize) the view that e-waste is hazardous, that it is waste and that it is undesirable.

Conclusions

In this chapter we have applied the concept of sociomateriality to e-waste in order to show some of the potential contradictions in and unforeseen consequences of current e-waste regulations and their attempt to fix problems. Examining these issues through the lens of hybridity helped our analysis and brought us closer to ways of resolving these contradictions. The discussions of Germany and South Africa above should not be taken as points from which to generalize about e-waste in the North and South. Instead, the use of these two case studies provides examples of different configurations of the social and material and of policy and practice. In line with our understanding of hybridity and relationality, e-waste policy and practice in these two countries must be seen as the outcome of a particular socioeconomic moment in a particular place. Nonetheless, there are lessons to be learned from this examination, primarily in terms of building our understanding of waste and our ability to analyse it as a dynamic hybrid. We do not consider this to be an exhaustive study, but hope instead to have shown the potential relevance and application of this type of research.

In our case study of Germany, we have seen an attempt to reshape practice through changes in policy. The two policies we discuss had different emphases and provide different responses to the problem of e-waste export. Both have been relatively ineffective in changing practice, in part, we argue because neither considers the distinctive, dynamic sociomateriality of e-waste. The meaning of waste remains relative to positionality – it is waste for some in some places at some times – and is not changed by attempts to fix it through policy. Thus, while policies attempt to discursively reconstruct waste, they are not adequately grounded in the materiality of e-waste and consequently have little impact on practice. In South Africa, e-waste is clearly viewed from different positions; waste from the North is undesirably, while regional African waste is not. Changes in practice and regulation are being attempted primarily through eWASA and ITA PEG, and the founders and prominent members of these organizations explicitly and simultaneously recognize both the material value and material risks of e-waste. There is likely to be more change in e-waste practice in South Africa than in Germany, possibly in part due to the close relationship between manufacturers, recyclers and the government in South Africa. However, the response of various actors to this changing practice differs. For some, changes in practice discursively shift the meaning and desirability of waste. Thus, waste is viewed differently, based on where it comes from as well as how it can be processed and the associated risks and benefits of using it.

While the regulatory structures of these two countries recognize and negotiate the sociomaterial in quite different ways, there is a similarity in the politico-economic implications of any regulatory changes. These similarities are based on the material properties of e-waste, which have arisen out of particular social processes of design and production. In Germany there is a movement towards a division of labour in which higher value processes occur in the formal sector in the global North. In South Africa there is a simultaneous movement of high value processes out of the hands of the small informal sector and into established industries, particularly those with already significant market shares. Our preliminary indications suggest that the informal sector and small-scale businesses in both countries are likely to be included in low value manual dismantling and separation of e-waste.

Notes

1. We recognize that the application of such terms oversimplifies diverse regions of the world, but apply them nonetheless as a shorthand. Our example of South Africa suggests some of the obstacles of such a simplification on the issue of e-waste (see also Lepawsky and McNabb 2009).
2. Although Douglas' actual text says "uncleanliness" her general arguments and common references suggest this is more widely true.
3. To impute agency to the non-human world is not to argue that a cell phone, for instance, consciously imposes its will on others but rather to unsettle the pervasive yet implicit assumption that agency is entirely a product of the mind. In other words, we note that nature (or in our case electronic goods) "influences and constrains human actions, but also the way that particular environments [and in our case technological artefacts] shape human intentions" (Nash 2005, 3).

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Part II

E-waste and the informal economy

2

E-waste management: Sustainable economic growth or inequitable distribution of environmental health risks?

Hiromi Inagaki

Introduction

Since the 1990s several member states of the Organization for Economic Co-operation and Development (OECD) have enacted landmark legislation on domestic e-waste management, but it is often reported that large quantities of e-waste have been shipped from OECD countries to developing countries in Asia and Africa for recycling and disposal (Levinson et al. 2008). As the former chief economist of the World Bank has noted, the economic rationale behind this is that "people value a clean environment more as their income rises, if other things are equal, costs fall if pollution moves from rich to poor ones" (Anand 2004). Given this economic rationale, who is responsible for the costs and damage generated by treating end-of-life products that are consumed by the rich but recycled by the poor? In addressing this point, we must consider a number of issues, including how environmental health risks from e-waste management are generated and distributed at the global level as well as in developing countries; who the most vulnerable people suffering from environmental health risks are and the underlying causes of these risks. Without addressing these questions, key issues could be overlooked in the policy-making process on e-waste management. Moreover, established policies would not capture the actual causes of environmental health risks, and they could not allocate responsibility for them.

Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
United Nations University Press, 2013, ISBN 978-92-808-8035-9

Research objectives

The objectives of this chapter are to (i) investigate how economic benefits and environmental health risks generated from e-waste recycling are distributed and structured at global and national levels and (ii) critically analyse how the policies and policy processes affect the distribution of economic benefits and environmental health risks.

Methodology and limitations

The research was conducted through a case study on computer waste (PC waste) flowing to and within India. India is one of the major destinations for shipping e-waste. The study focused on PC waste because of its two opposing dimensions: its potential as an economic resource and its toxicity. While the computer sector is the fastest growing information technology sector in India (Tata Energy Research Institute 1999, cited in Mundada et al. 2004), computers can pose environmental health risks unless they are properly managed. India was selected for this study because of the visibility of PC waste recycling activities there. The term "computer" used in this study includes both laptop and desktop computers.

This study draws on both secondary data from existing studies and Indian national policies on e-waste, and primary data collected in interviews. Semi-structured interviews, both face-to-face and by telephone, were conducted with different actors in e-waste recycling chains in and outside India. These included importers, repair and resell shops, traders, street vendors, dismantlers and extractors of raw materials in India, a Belgian smelting and refining company and Dutch, German and Indian e-waste expert organizations. Qualitative data analysis was also implemented. A quantitative analysis was found to be unnecessary as this chapter does not aim to generalize economic profits and environmental health risks.

E-waste policy development processes were not examined in depth due to the limited period of my 3-week field research. I was able to participate in only one national workshop but followed it up with further investigation by conducting interviews with non-governmental organizations (NGOs) and government officers who participated in the workshop. Time limitations and language barriers also constrained the number of interviews.

Analytical framework

The study was implemented through an analysis based on an environmental justice (EJ) framework that emphasizes the distributional implications of environmental change with a focus on broader social justice issues. The principle behind the claim is that people and communities with a low income bear a disproportionate share of the burden of environmental health problems in the form of toxic waste, health risks and unsafe jobs, while many of the rich benefit from better health (Blowers 2003; Foreman 1998; Kraft and Scheberle 1995; Ringuuist 1997, cited in Anand 2004). Within the EJ framework are two dimensions: distributional and procedural justice (Anand 2004). Distributional justice deals the multiple relationships exercised in different socio-political contexts, allowing for the examination of how an inequitable distribution of environmental health risks is associated with "relations between people, within and between groups of people, and between people and their natural, cultural, social, political and economic environments" (Hallowes and Butler 2002, 52). Procedural justice examines decision-making processes from the perspective of the equal participation of different groups of people.

When applying the EJ framework, four key elements need to be examined: the social differences between actors, the spatial characteristics of the problem, the multi-level causality of the environmental issue and its effects through space and time. Firstly, not only ecological issues but also the different social backgrounds of people need to be taken into account to ensure the inclusion of all groups affected, such as those from the lower castes and migrants. Otherwise, the interests represented will include only those from the elite and middle class who wish to prevent environmental damage in order to maintain their pleasant surroundings, resulting in the diversion of polluting projects to disadvantaged communities (Blowers 2003). In addition to social differences, EJ theorists argue that specific places that are exposed to environmental health risks are disadvantaged (Blowers 2003). Capital tends to hold the superior command over space, for example, by taking advantage of labour's relative immobility and limited spatial options (Ruiters 2002). Furthermore, the multiple causality of an environmental problem needs to be accounted for. Environmental health effects in one locality can lead to regional, national and transnational effects elsewhere (Blowers 2003). Lastly, the effects of environmental change over space and time need to be examined. It is possible that current polluting activities will transmit environmental effects down generations and across places (Blowers 2003).

Results of analysis

Distribution and structure of economic benefits and environmental health risks in global PC and PC waste flow

Figure 2.1 illustrates how economic benefits and environmental health risks are distributed and structured in the global flow of PC and PC waste. Economic benefits are unevenly distributed to global companies that control the flow of PCs and PC waste using their huge financial capital for research and development (R&D). International software companies gain huge economic benefits by controlling the upgrading cycle of PC software to ensure that sales from software licenses remain high. According to a retailer I interviewed, consumers purchase a new PC every two to three years because of the technical incompatibility between the hardware components (e.g. the central processing units) of their PCs and new software (e.g. Windows Vista) that is regularly upgraded and installed by software companies (personal communication, 30 July 2008). The regular upgrading of software promoted through R&D results in increases in the volume of end-of-life PCs, the frequency of recycling activities and subsequent environmental health risks. As conceptualized in the notion of extended producer responsibility (EPR), however, the responsibility for paying for the negative externalities is placed on a producer, that is, hardware companies in the case of the PC industry. Or, in some cases in India, the environment and health risks continue to fall on recycling workers and neighbouring communities. Hence, economic profits are continuously being distributed to globally separate software companies.

Apart from international software companies, global refineries equipped with energy-efficient clean technologies also gain huge profits from the monopolistic price determination of the PC waste traded and precious metals refined in business negotiations with Indian recycling companies. The global refineries can exercise their bargaining power over the type, price and flow of precious metals because no clean technology is available for it and no established standard for determining the value of recovered and refined precious metals in India (personal communication, Umicore 3 September 2008).

By contrast, the environmental health risks of PC waste are concentrated in the recycling industry in India. This uneven distribution of benefits and risks in the global PC and PC waste market is attributed to the monopolistic control and economic clout of global corporations over the material flow of PCs and PC waste, forcing the recycling industry in India, that has less economic power, to depend on the former in order to make a profit.

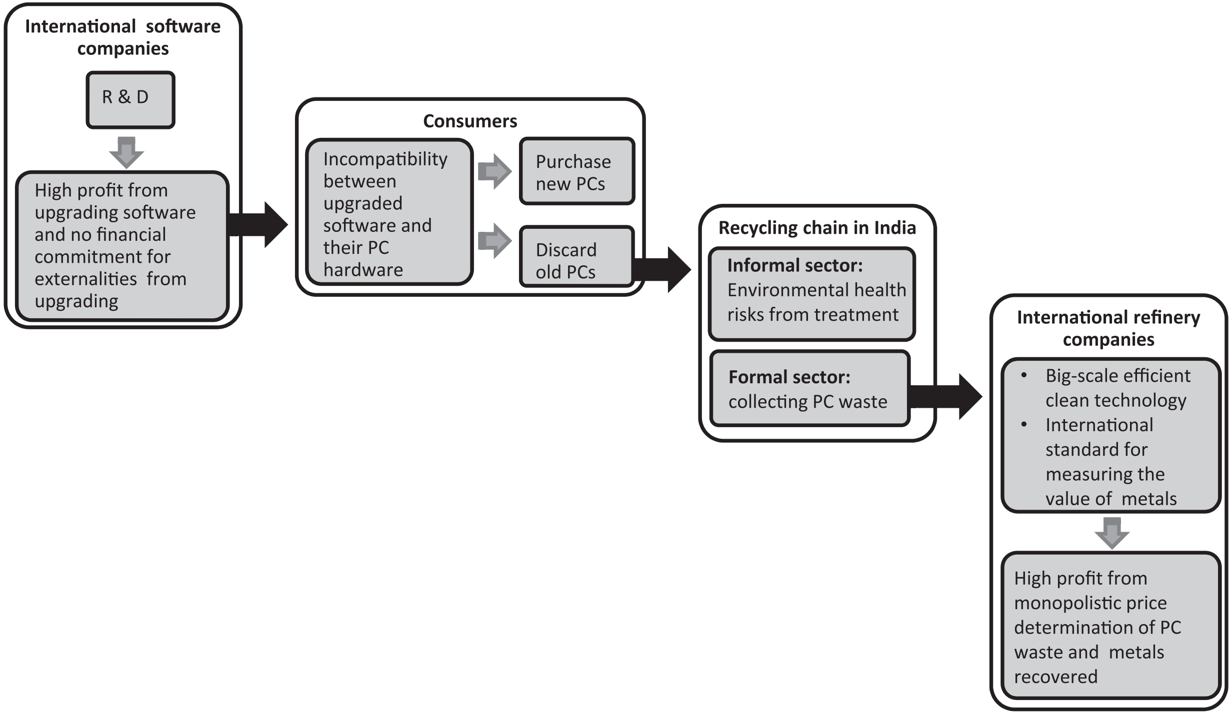

Figure 2.1 Distribution and structure of economic benefits and environmental health risks at global level

Distribution and structure of economic benefits and environmental health risks in the informal PC waste recycling chain in India

Turning from the global to national level, we see that economic benefits and environmental health risks are disproportionately distributed within India as well. As approximately 95 per cent of the total e-waste that enters the recycling industry in India is handled by the informal sector and more than 60 per cent of this is PC waste (IMRB International 2007), the analysis is focused on the informal sector. In the informal sector[1] the actors can be identified by their recycling activities in the value chain of PC waste, that is, big traders, small traders, collectors, dismantlers, extractors and smelters.

Distribution and structure of economic benefits and environmental health risks between traders and recyclers

Figure 2.2 shows how economic profits and environmental health risks are distributed and structured in the multifaceted, dynamic relations between traders and recyclers. Traders gain great economic profits, mainly by exercising their bargaining power over the types and flow of PC waste, as well as by accepting bribes from recyclers.

However, recyclers shoulder the burden of environmental health risks from their activities in dismantling, extracting and smelting PC waste. This disproportionate distribution of benefits and risks in the informal sector can be attributed to the unequal power relations by which recyclers are economically and socially dependent on the traders. Figure 2.2 shows the determining factors that contribute to structuring these power relations. They include the differences in the parties' financial and spatial assets, their social status in the network and their access to profitable formal economic systems (e.g. auctions and the secondary market).

Big traders earn substantial profits by utilising their financial assets to import and purchase at auction the bulk of newer models of PC waste, most of which still contain functional and valuable components and are hence re-sellable to secondary markets at a high price. Small traders equipped with spatial assets and access to secondary markets can purchase PC waste from big traders, store and separate it into working and non-working PCs and parts, and refurbish and sell the working PCs to middlemen or secondary markets at a high price.[2] Meanwhile, the recyclers, including the collectors, dismantlers, extractors and smelters, can only purchase the less valuable non-working PC waste from the small traders. In some cases the recyclers obtain access to low-value PC waste by bribing the traders. In addition, traders can continuously control the whole recycling chain by the application of their social status. According to interviewees, most scrap-related traders and recyclers in Delhi are

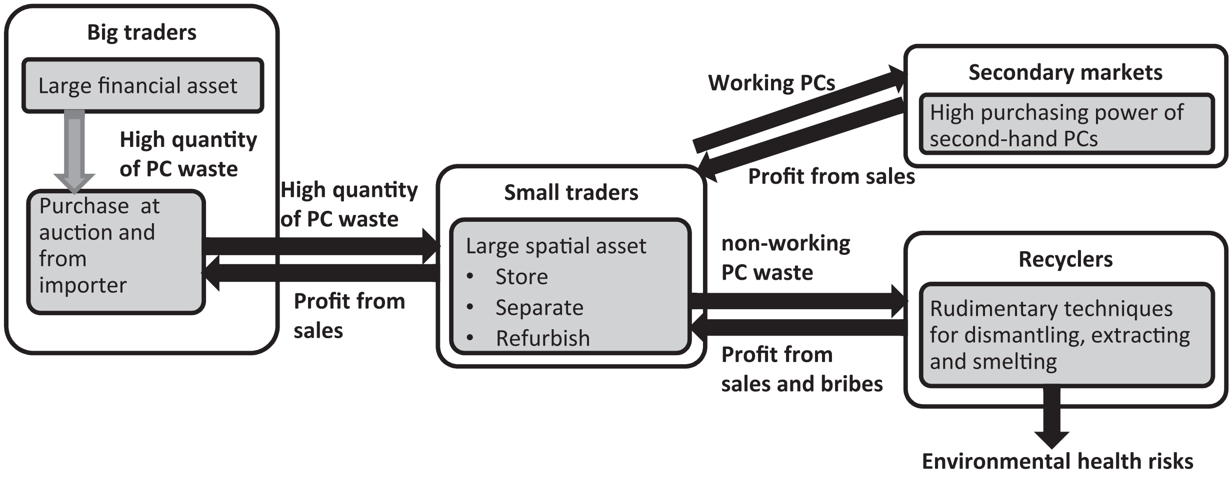

Figure 2.2 Distribution and structure of economic benefits and environmental health risks in informal recycling chain in India

Muslims who are socially connected along the chain of recycling activities in a hierarchical feudal network. The traders do not seem to allow outsiders or non-Muslims to join the scrap trading business. While this trade is becoming visible and attractive to Hindi traders, it is difficult for them to gain access to it because big Muslim traders control the flow of PC waste within their network (Toxcis Link, personal communication, 15 September 2008).

While traders benefit economically, recyclers suffer from environmental health risks. They are exposed to these risks during the processes of treating the hazardous substances contained in e-waste. In most cases in India, dismantlers, extractors and smelters are exposed to these risks because they use rudimentary techniques to treat the e-waste. In the dismantling process, workers, including children, work in sheds that are insufficiently ventilated; they do not use protective equipment such as masks, and they are in constant contact with toxic materials in the machines. Their long exposure to hazardous substances is likely to induce chronic disease (Basu, 2008). By hammering down e-waste components, dismantlers endure high levels of noise which slowly impairs their hearing (Sinha 2008). Small pieces of plastic residuals thrown into the streets could eventually cause environmental degradation in the surrounding areas. In the extracting process workers work with acid baths, applying caustic soda by hand and using open burning to recover copper. They are very vulnerable to the acid fumes and toxic gases that endanger their health (Agarwal et al. 2003; Basu 2008).

Distribution and structure of economic benefits and environmental health risks between owners and workers or residents

At the micro-level we see that the recyclers' social and economic dependency on the traders further configures the complex relations between owners and workers in a recycling unit and between the recycling industry and residents in peripheral areas in Delhi, distributing economic benefits and environmental risks among them unequally. As Figure 2.3 shows, there are determinant factors that contribute to structuring this uneven distribution. These are the workers' social and spatial disadvantages.

Owners control the urban poor in Delhi who flood in from other states in India to find work. They do this by wielding their one-sided bargaining power when they take on casual labour. On their part, workers place their own health at risk in favour of secure employment, which is hard to find because of their social insecurity and spatial immobility. As mentioned by one interviewee, some workers do not belong to the feudal caste system nor do they have legal status because they are illegal migrants from other parts of India or Bangladesh. Hence, they are unable or unwilling to express the difficulties they encounter deriving from their

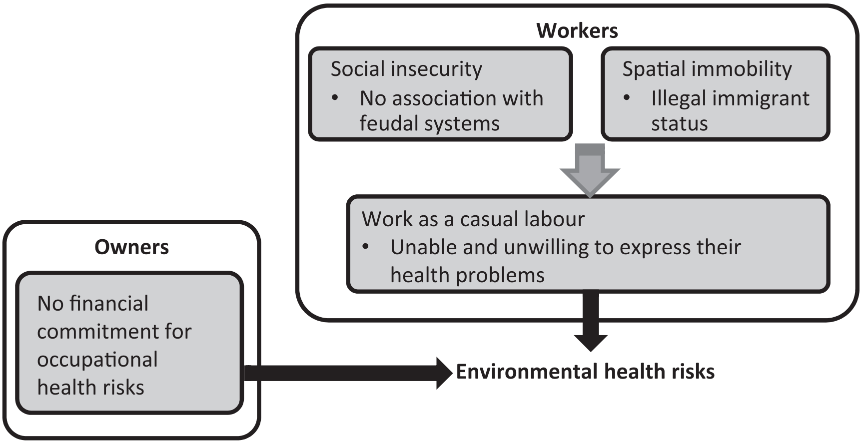

Figure 2.3 Distribution and structure of environmental health risks in recycling units

health problems. Owners do not expect to pay for these externalities generated from their recycling business.

In addition to the disproportionate distribution of environmental health risks between owners and workers, we see that residents in surrounding communities also face these risks as a result of the owners' political and economic coalitions that take advantage of the spatial characteristics of these communities. The most hazardous activities; dismantling and smelting raw materials, are nowadays often seen in peripheral areas of Delhi that are geographically remote and relatively inaccessible. According to one interviewee, the recycling units were pushed out of residential areas in central Delhi to a border region with a neighbouring state where the economic interests of owners, the authorities and landowners were realized through their mutual political connections.

This new formation or expansion of recycling units in peripheral areas, meanwhile, creates ecological refugees; local residents who are forced to leave their homes in search of access to potable water in other areas (Basu 2008). This is illustrated by the survey implemented by the Energy and Resources Institute (TERI) on the environmental health impacts of e-waste recycling in Mandoli village. The TERI found that the concentration of all metals in the soil was much higher in the industrial site than in other sites of the village and that the groundwater, the only source of drinking water for the villagers, was heavily polluted (TERI, 2006, cited in Basu 2008). Hence, the residents, who had lived in this area long before the recycling industries were established, were facing a scarcity of fresh drinking water (Basu, 2008). Furthermore, the concentration of dioxin and furan in the air was reported to be four to six times greater than the upper limit set by the World Health Organization (Basu 2007, cited in Basu 2008). As a result, approximately 200 families were obliged to leave the area, thus becoming ecological refugees (Basu 2008). In other words, the hazardous activities of the unwanted recycling industry are reinforced by the economic coalition of owners and authorities, resulting in environmental degradation (Blowers 2003).

Effects of policies and policy processes on the distribution of economic benefits and environmental health risks

Policy on e-waste management

In 2010 the Indian Ministry of Environment and Forests (MoEF) issued a draft ruling on e-waste management called the "e-waste (Management and Handling) Rules 2010" (MoEF 2010), which came into effect on 12 May 2012. The rules are premised on an EPR approach, in which "a producer's responsibility is extended to the post-consumer stage of a product's life cycle" (OECD 2010). Under this rule, producers have responsibilities for collecting e-waste by setting up collection centres or a take-back system "individually or collectively" and financing "a system to meet the costs involved in the environmentally sound management of e-waste" (MoEF 2010). The MoEF regulates the registration of companies and individuals involved in e-waste management and authorizes their activities.

This legislation creates space for a producer to seek profit-oriented and market-driven solutions to e-waste, such as subcontracting e-waste collection or treatment systems to formal recycling companies. These subcontracted recycling companies subcontracted seek profit-oriented solutions as well for running the collection or treatment systems. As at 2008, all the registered recycling companies in India had to outsource the PC waste recovery and refinery treatment to global refineries because they did not comply with the standards of environmentally sound technology defined by the MoEF. This treatment service outsourced costs but the Indian recycling companies intend to recover the cost by selling to international markets at a high yield the highly valued metals recovered and refined by the global refineries. The premise is that the more PC waste is recovered, the more the cost is reduced. The recycling companies' intention to achieve economies of scale drives them to build a particular partnership with the informal sector that allows them to collect a high quantity of e-waste. One of the recycling companies I had interviewed confirmed that this partnership can sustain profitability.

However, this market-dependent profit-making solution to waste has socioeconomic implications for the informal recycling chain in India. An informal group of 17,000 waste collectors and recyclers who been in partnership with formal recyclers revealed that they had been requested to collect but not to dismantle as many brand-labelled PC waste as possible.

This partnership between the formal and informal sectors implies that the labour-intensive dismantling activities that take place in the informal sector may now be cut off from the chain, which could lead to the loss of employment by the dismantlers, extractor and smelters or their having to accept lower wages as PC waste collectors. Given the socioeconomic, spatial and political disadvantages that recyclers in the informal sector face, there is no assurance that this partnership will make all informal workers economically better off than they are at present.

Apart from its impact on the economic benefits available to poor workers, this market-driven partnership between the formal and informal sector needs be challenged in terms of freeing the poor workers from the environmental health problems they suffer. Two of the formal recycling companies that I interviewed mentioned that they it would be economically advantageous for them to collect specific PC waste components. Hence, the non-economic components and residuals (e.g. plastic pieces) obtained by dismantling PCs might remain in the hands of poor workers, and be treated in neither a safe nor environmentally friendly manner. In other words, the EPR policy and its by-product, the partnership of the formal and informal sectors; seem to lead to the exclusion of some informal recyclers from making a profit and the incomplete attention to environmental health hazards.

Policies on importing second-hand computers

Importing second-hand computers is strongly encouraged by Government of India as these products can be used. The e-waste (Management and Handling) Rules 2010 permit the importation of used electrical and electronic equipment to India as long as "it is imported for the purpose of repair or refurbishment or to fulfil obligations under EPR" (MoEF 2010). In addition, the Indian government permits the import of second-hand PCs (PCs less than 10 years old), for the purpose of reuse, together with non-functioning PC waste for recycling if it is considered as raw materials.[3] These policies on the importation of second-hand computers comply with the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention, UNEP 1989). The Basel Convention regulates the export and import of PC waste but allows the transboundary movement of PC waste when "required as a raw material for recycling or recovery industries in the

State of import" (Article 4, 9 (b) of the Basel Convention) (Arts and Gupta 2004). Furthermore, at an international conference in 2002, South Asian countries formulated a strategy that would promote the use of e-waste, including PC waste, as raw material for their economic development (Iles 2004).

Promoting the import of second-hand computers leads to an increase in the volume of e-waste, placing environmental risks on poor workers. The more second-hand PCs that flow into the secondary market, the lower the price of new PCs in the primary market become in order to compete with the second-hand PCs. Consequently, this leads to the broadening of access to relatively cheap PCs among a wider population range with different income levels, while causing an increase in the volume of e-waste in India. While some gain economic benefits from this access to second-hand PCs and the use of the raw materials extracted from PC waste, recycling workers and local residents continue to suffer from environmental health hazards, with little economic benefit.

Policy-making processes for e-waste management

Through my participation in a national consultation workshop on preparation of an e-waste policy and interviews with key Indian NGOs in 2008, I noted that traders were included and workers and local residents were excluded from the policy-making process. The incorporation of the traders at the top of the informal recycling chain in formal e-waste collection was articulated as a key for making an e-waste policy effective. Meanwhile, the recycling workers and local residents in a community who suffer from these recycling activities were not represented in the policy-making process. The workshop participants used terms such as "informal sector", "recycler" and "dismantler", to lump owners and workers, migrant workers and lower class Muslims and Hindus all into the same category. In addition, some of the NGOs that were making efforts to address the perspectives of this "informal sector" at the workshop seemed to overlook the social, economic and spatial characteristics of workers, residents and local communities. For example, one NGO officer remarked that was no difference in social status among the Muslim recyclers. This misunderstanding by an NGO officer which works closely with recyclers at the bottom of the hierarchy is critical for the policy-making process, as it can result in not only excluding the voices of most vulnerable groups from the policy arena, but also in overlooking social, economic and spatial issues underlying environmental health problems that might ultimately become an obstacle to effective policy-making.

The uneven distribution of economic benefits and environmental health risks between people with and without bargaining power are not challenged in the policy-making processes. Depending on which category of "informal recyclers" is referred to by policy-makers, the issues that are found to be problematic vary, and thus urgent issues such as environmental health hazards for workers and local residents may be excluded from policy-making processes.

Discussion and conclusion

Economic benefits and environmental health risks from e-waste recycling are unevenly distributed in dynamic relationships at global and national levels. These are relationships between global software manufacturers and refineries and the Indian PC waste recycling industry, between traders and recyclers in the informal e-waste recycling chain and between owners and workers or residents in a recycling unit in peripheral areas. While the former in each relationship gain high economic profits, the latter suffer from environmental health risks. This disproportionate distribution of benefits and risks within each relationship is associated with the financial, spatial, social and political assets of the former that enable them to control the volume, type, price and flow of PC waste and the precious metals contained in PC waste.

Despite this inequitable distribution of economic benefits and environmental health risks, Indian e-waste-related policies and policy-making processes do not provide any space for addressing this issue. This can be attributed to the government's choice of tools to prioritize sustainable economic growth. Firstly, the EPR approach, upon which the e-waste (Management and Handling) Rules, 2010 were based, shifts the responsibility for establishing environmentally sound management of e-waste from the government to the private sector and the market. The nature of the EPR policy has also been noted by the OECD (2010). Consequently, the private-sector focused approach seems to place more attention on the market, business and its key players, rather than the economically disempowered working poor at the bottom of the recycling chain or the underlying causes of their disempowerment, including their socio-political and spatial disadvantages.

Secondly, national policies on economic growth seem to have accelerated the transnational flow of e-waste to India, allowing the import of second-hand PCs as raw material but not creating a policy on redistributing the economic benefits of doing so, such as by providing free health care to those who suffer from the health hazards caused by recycling activities. As implied by Iles (2004), the development model that India seeks can induce conditions that benefit those with bargaining power and who can profit from recycling PC waste, which is conducted by the working poor under their control.

The failure to address the issue of equitable distribution in policy arenas poses further theoretical implications. The abovementioned policies are underpinned by the ecological modernization concept whose fundamental principle is expressed as "economic growth and the resolution of ecological problems can, in principle, be reconciled" (Hajer 1995, cited in Blowers 2003). However, two key features of EM need to be challenged: that of seeing the market as efficient and responsive to environmental problems and placing the responsibility of environmental services on the private sector, and that of formulating an environmental policy through a partnership between the state and business (Blowers 2003). As explained above, the EPR neither addresses the environmental health risks caused by e-waste management nor provides economic benefits to all the actors involved. This implies that a market-oriented solution to e-waste management by itself cannot lead to the reconciliation of economic growth and improve environmental health. In addition, if the nexus of state and business is the only factor taken into account in policy-making arenas, socio-economic, spatial and political characteristics embedded in the dynamic relations between people and between environments will be overlooked, preventing the harmonization of economic growth and ecological problems. Hence, government intervention is required, in which special attention is placed on inclusive governance, especially for those who suffer the greatest burden of environmental health risks.

Notes

1. In this chapter I employ Narayana's definition of informal and formal sectors. The informal sector is unorganized and comprises enterprises that (i) engage in the production and/or distribution of goods and/or services meant for sale; (ii) operate under the proprietary or partnership ownership categories; (iii) employ fewer than 10 workers and casual workers and (iv) are not under any obligation to maintain a regular account on their activities (Narayana 2006). The formal sector has none the characteristics of the informal sector.
2. Most auctions of e-waste are carried out alongside other scrap such as office furniture and hand tools. Whoever buys computers must purchase the whole lot (IMRB International, 2007). The selling price consists of the minimum auction price and a deposit to participate. At an auction held in 2002 the price set for 29 computers, 24 printers six TVs and other electronic goods was Rs30,000 (Agarwal et al. 2003), including the deposit, was calculated as Rs 86,332. By dividing this sum by 59, the total number of items, and assuming that the obsolete computers, printers and TVs had a similar value, each item was sold for Rs1,463, which converts to US$29, using the average exchange rate as at February 2002. The price of the newer second-hand models sold at the secondary market ranged from Rs5,000 to Rs15,000 at the time of the survey in February 2002 (Agarwal et al., 2003). By using the same exchange rate (1INR=0.02US$), the figures were corrected to between US$100 and US$300. Comparing the selling prices of PC waste at an auction where functioning PC waste is sold (US$29) and at the secondary market where repaired

and refurbished PC waste and its components are sold (US$100–300), we see that big and small traders add value and gain relatively high profits.

3. Stated in Schedule 3 of the Hazardous Wastes (Management and Handling) Rules 2003 issued by MoEF (2008).

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3

Rise of informalization in global capitalism: Exploring environmental sustainability in e-waste management

Somjita Laha

Introduction

Contemporary economic operations are carried out increasingly in the informal economy where large parts of all production, distribution and exchange take place. In the more recent history of the evolution of capitalism[1] the informalization of the production process constitutes an important development. The practice of informalization forms an integral part of the contemporary capitalist production system and its accompanying socioeconomic organization. A propensity to avoid tax and labour regulations encourages the process of informalization of economic activities (Gallin 2001; Pearson 2004; Standing 1989). The key motivation behind informalization is the evasion of stringent regulations for continuous profit generation and surplus accumulation, which is necessary for the expansion and reproduction of capitalism. In this chapter, the way in which capitalism escapes environmental regulations using informalization is highlighted with the case of e-waste.

The chapter starts with the concept of the informal economy in which the process of informalization is theoretically situated. The next section deals with the relationship between informalization and the environment, focusing on the contradiction between informality and the successful implementation of environmental regulations. Thereafter, the issue of the informalization of e-waste management in the context of capitalism is elaborated and the transboundary movement of e-waste is examined. Here, the various international, regional and national initiatives to control such

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movement are analysed and the notion of extended producer responsibility (EPR) is discussed. Subsequently I examine the different reasons for the flow of waste, linked to the concept of environmental justice, which is breached in the following section. Finally the chapter highlights two dominant trends in contemporary capitalism that contribute to the growth of electronic and electrical equipment (EEE) production and consumption, leading to mammoth volumes of e-waste generation. The argument is summarized in the conclusion.

The informal economy and informalization in contemporary world development

In previous years the informal sector was perceived to be an incomplete expression of capitalist development that would disappear with industrial advancement. According to Marxist and neo-Marxist theories, the informal sector constituted the reserve army of labour that would be absorbed by the expansion of the modern capitalist system (Gerry 1987). Or, following the postulates of Lewis' orthodox development theory, once development received ample impetus, the modern economy would grow and swallow the surplus labour along its periphery (Sanyal 2007). But the continued persistence of the informal sector in both developed and developing countries and the analysis of the structural causes of informality suggest that the sector is in congruence with the regime of modern capitalism (Portes and Sassen-Koob 1987; Sassen 1994).

Contrary to the earlier theories that predicted that the informal sector was a temporary phenomenon or a vestige of the pre-capitalist era (Light 2004), the modern informal space is an enduring and dynamic extension and complement to the formal capitalist sector in the production and distribution of goods and services. Though in its nomenclature and conceptualization the informal economy consists of the opposite of the formal economy, the two sectors function together as two sides of the same coin in the advance of capitalism; with the informal sector being unregulated, unorganized, unrecorded and often invisible (Weiss 1987). Therefore, the workings of the informal sector are often well within the control of global capitalism. Sanyal (2007) views the informal economy as a product of capitalist development; it is the "internal other of the modern capital". To further its profit-oriented goals, the formal economic sphere directly encourages the growth of the informal sector by the informalizing strategies adopted in the course of production, like cost minimization, avoiding organized labour and evading regulations. Informalization thus should be understood as a structural tendency of capitalist expansion (Murray 1983), which has been promoted to augment and reproduce capitalism and protect it against potential shocks and crises. The phenomenon of informalization is knitted closely into the fabric of the modern capitalist economy (Portes and Schauffler 1993; Stark 1989) in which informal activities are functional to and marginalized by this economic form.

There has been an increasing trend towards informalization spanning different sectors worldwide (Carr and Chen 2001; Meagher 2008) since the beginning of the economic crisis in the mid-1970s (Meagher 1995). Informalization embodied a reorganization towards flexible production relations, leading to processes of labour casualization and contractualization (Standing 2008) and a rising share of informal jobs in the total employment edifice (Heintz and Pollin 2003). This new international division of labour emerged out of a need for cheaper labour in the course of decentralization and flexible production brought about to sustain profitability in the face of competitiveness and uncertainty in the world market (Benería 2001). The prospect of flexible specialization with post-Fordist restructuring of economic production intensified the phenomenon of informalization that replaced the vertically integrated production structure of the Fordist regime.

This coincided with the advent of neoliberal ideology promoting deregulation and privatization in the labour market[2] after post-war Keynesianism in mainstream development policies was called into question following the economic recession of the 1970s and the crisis of the welfare state regime (Ghezzi and Mingione 2003). Fixed-wage formal employment was reduced and more flexible systems of subcontracting and outsourcing surfaced, making use of unregulated labour in the form of casual, temporary, off-the-books workers (Standing 1989). Thus "capital ... abandoned reciprocal obligations to labour in employment contract" (Robinson 2004) and there was a group of workers who were unprotected and had no job stability, non-wage benefits, pension, compensation or insurance against hazards and accidents in the workplace.[3] Less state intervention in favour of market rationality saw huge cutbacks in public sector employment and investment and a sharp decline in government spending. Unemployment soared and people were pushed into the informal sector in the absence of adequate formal work opportunities (Kumar 2007).

The subsequent removal of trade barriers and export-led industrialization paved the way for globalization, marked by the ascendancy of transnational capital (Robinson 2004). Informalization became interwoven in the progressive integration of different parts of the world into one global economy in which multinational production processes were successfully decentralized across (and within) national boundaries. Globalization championed the free exchange of capital across borders, which allowed for the internationalization of production leading to a fragmentation of supply chains (Pearson 2004) across countries that involved outsourcing work through independent contractors hiring informal labour. The transnational enterprises frequently acted as organizers of the production that others carried out for them (Gallin 2001). Hence, labour costs were decreased and the risks of production were passed on to the informal worker, who was dependent on but not part of the formal production structure, as the multinationals were not obligated to labour and followed the dictates of the volatile international market. Thus, the informal sector was integrated in the domain of international production and exchange, making informalization a global phenomenon.

Hence, it is evident that the informal economy will not cease to exist with capitalist industrial development. Informalization is a consequence of modern capitalism, not a transitory path towards advanced industrialization. It is not a temporary phenomenon; it is an essential by-product of capitalism in which formal production is the hegemonic form of the capitalist system that informalizes large segments of its production to facilitate the reproduction of the modern capitalistic world order. According to recent figures, the informal sector accounts for 33–40 per cent of urban employment in Asia, 60–75 per cent in Central America and 60 per cent in Africa (Sanyal 2007).

Environment and the process of informalization

Traditionally, concerns for nature and the environment have been relegated to the margins of human priorities. But escalating environmental problems over the recent decades have accorded environmental issues unprecedented primacy internationally (Adams 2001). This has led to the rise of environmental regulations worldwide which aim at achieving environmental sustainability in all economic processes (Brundtland 1987). However, the current increase in informalization makes it impossible to properly implement environmental regulations since informal sector activities by their very nature are not amenable to existing systems of regulations (Blackman 2000). Mounting environmental concerns have been matched by deregulation in the economic processes (in the form of informalization), which places a substantial portion of economic activities outside the domain of any regulation. Hence, the entire framework of environmental regulation has been rendered futile and ineffective in the face of the process.

Informalization has not been yet studied in the context of the environment. This chapter locates the increasing trend of informalization in the global capitalist order and studies its environmental contradictions with respect to e-waste management in the informal sector. The informal sector is not an autonomous segment of the economy but is necessarily created by and is subordinate to the formal capitalist system. The informal sphere often functions as a cover under which formal capitalism hides its anomalies from the regulatory institutions; one of the anomalies of capitalism being the enormous environmental degradation that it unleashes.

The primary emphasis of the environmental sustainability framework is on the formulations of suitable regulations, incentives and standards to arrest the rate of environmental degradation (Redclift 1987, 2005). But a substantial part of the economy escapes regulations through informalization. While the visible end of the spectrum (as reflected by the formal economy) is adjudged on its sustainability parameters, the often imperceptible linkages that it shares with the informal economy are overlooked. By a systematic move towards informalization, the capitalist production system conceals its aversion of rules, regulations and standards (all of which prey on profit margins). Because of their inability to address the phenomenon of informalization, mainstream environmental policies are unable to deal with a major part of environmentally harmful activities. Hereafter, the case of electronic and electrical waste (e-waste) is discussed to show the movement of EEE from the regulated formal economy to the unregulated informal domain.

Informalization of e-waste

Current consumption patterns in a rapidly urbanizing world have rendered waste management a global environmental concern. E-waste is the latest challenge to the issue of hazardous waste management. A globally competitive electronic market has ushered in a range of attractive and cheap commodities readily consumed by the growing population in urban and peri-urban areas. Fast progress in information technology has led to the development and use of products with a very short lifespan. The rapid obsolescence of electronic goods aids the current trend of consumerism. Aggressive marketing strategies successfully target people with increasing purchasing power to indulge in the latest innovations in the field. New commodities continue being introduced to the market in growing frequencies and old ones are rapidly discarded. All this has culminated in the generation of massive quantities of toxic waste, leading to concerns about its suitable disposal and management.

E-waste results from a wide range of products like information technology and telecommunications equipment (like computers and mobile phones) as well as consumer equipment (household appliances like television, refrigerators and air-conditioners). The actual scope of e-waste is not clearly defined since different countries adopt different working definitions to categorize e-waste (Maxianova 2008; Widmer et al. 2005; Williams 2005). But there is no doubt about the enormous scale of e-waste creation: in the industrialized world it constitutes the fastest growing waste stream.

The problem of e-waste management is not merely manifested in the developed world. Through illegal scrap trade and export, huge volumes of e-waste reach developing countries, which constitute the major centres of e-waste disposal and recycling. The domestic consumption of EEE has also increased in the developing world recently. Although in industrializing countries like China and India per capita consumption lags far behind that in the developed nations, given the population figures, the e-waste emerging domestically in these countries is reaching mammoth proportions (Widmer et al. 2005). A disproportionate share of the environmental burden of e-waste processing in those countries is borne by the poor and marginalized sections of the population who are involved in this task in the absence of other gainful livelihood options.

The bulk of electronic consumption occurs in the developed nations, but the resulting waste is exported mainly to countries in Asia (primarily China and India) to avoid expensive recycling and disposal in the country of use and comply with its stringent environmental regulations (Yap 2006). The availability of cheap labour and the absence of rigid environmental and health regulations provide a congenial atmosphere for dumping e-waste in Asia (Puckett and Smith 2002). E-waste segregation and disassembly are extremely tedious and labour-intensive processes in which workers often employ crude, primitive tools and techniques to extract the valuable components. These backyard industries regularly use manual household labour, where women and children take apart small and intricate components by hand. Some discarded pieces of electronic equipment, especially computers, are in a reusable condition and enter secondary markets in these developing countries to provide low-priced options for people unable to afford brand new products. E-waste processing is also a lucrative income-generating activity, the economics of which bring in willing traders, recyclers, scrap-dealers and dismantlers who do not necessarily have adequate knowledge of the associated hazards. The international material flow of e-waste is practically impossible to quantify, as a large part of this trade is hidden under the official radar.

Thus, the capitalist order hides the enormous quantities of e-waste it generates in overseas shipments to countries where the waste moves into the informal economy. While the benefits from EEE production and consumption accrue to the formal sector, the informal economy is left with the job of cleaning up the waste. By shirking the responsibility of waste treatment in appropriate and expensive ways, the formal sector inevitably triggers the informalization of waste, whereby the e-waste stream is typically channelled into the unorganized, unregulated and often invisible informal domain. With regard to e-waste, the practice of informalization is a "wider economic response to the crisis" (Meagher 1995) of massive increase of toxic e-waste production in recent times.

Addressing the transboundary movement of e-waste

Both at the international and the national level, there have been various attempts to control the illegal scrap trade. Systems of accountability have been envisioned to ensure that the producers or consumers bear the responsibility of e-waste management, since they also derive the benefits from sales revenue or consumption. However, such initiatives have been largely unsuccessful. The crucial global, regional and national policies and legislations are briefly described below.

Basel Convention and Basel Ban

According to the UNEP, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal constitutes the "most comprehensive global environmental agreement on hazardous and other wastes" (UNEP 2004). In the late 1980s, to counter the expensive waste disposal options at home resulting from stricter environmental regulation, the developed world resorted to dumping hazardous waste onto the developing countries (Yap 2006). The Basel Convention was established in 1989 and enforced in 1992 to combat this upsurge in the illegal export of harmful waste to less developed countries. E-waste was recognized as hazardous under the Convention in 1998. It requires all exporting nations to obtain prior permission from the countries of import and even transit, whether or not they are signatories to the Convention (Asante-Duah et al. 1992). It currently has 172 parties who are obliged to guarantee that the e-waste exported is handled and managed in an environmentally sound manner. In 1995 the Basel Ban Amendment was implemented to prohibit the export of illegal waste from developed to developing countries (BAN/SVTC 2002). Presently, with too few ratifications (28 countries), the ban has not come into force.

Ironically, one of the largest exporters of hazardous waste, the USA,[4] has signed but not yet ratified the Convention.[5] Even countries like Canada, Japan, Australia and South Korea, who are parties to the Convention, often flout it since it is not legally binding. Regularly junk materials (mainly computers) very close to their end-of-life are sent to the developing world in the name of charity or as donations since, unless they are destined to be recycled or disposed, EEE do not come under the

Basel definition of hazardous waste. After the Basel Ban, previously obsolete items are now coming in under the guise of usable products, which are exempted in the Ban (Shinkuma and Huong 2009). Moreover, scrap trade within Asia is not addressed by the Basel Ban (Iles 2004). For all these reasons, the Basel Convention and the Ban remain largely ineffective despite being the sole international agreements for trade in hazardous waste. The failure of the Basel Convention has led certain regions to adopt their own resolution.

Several countries at the receiving end have also formulated specific policies to curb the entry of toxic waste. In 1998 a summit of the Organization of African Unity[6] decided to ban all waste trade deals with the developed region. This decision has been extended into an African Convention on the Transboundary Movement of Hazardous Waste and their Disposal which prohibits all types of waste shipments to the African continent (Asante-Duah et al. 1992). In 2000 China and in 2001 Vietnam totally banned the import of second-hand EEE (Shinkuma and Huong 2009). In 2004 Vietnam forbade the import of e-waste scrap and later prohibited its dismantling. India, one of the major recipients of e-waste, at the time of writing had no legislation on the entry of e-waste to its territory.

Extended producer responsibility (EPR)

Based on the "polluter pays" principle, the concept of EPR strives to make the manufacturers accountable for the environmental impact of their consumer products. The definition of EPR, according to Organization for Economic Cooperation and Development (OECD), is "An environmental policy approach in which a producers' responsibility for a product is extended to the post-consumer stage of a product's life cycle including its final disposal" (Nnorom and Osibanjo 2007; Widmer et al. 2005).

In the early 1990s the term EPR was first coined by Thomas Lindhqvist. Through the implementation of EPR, producers would have the incentive of using more environmentally sound products or designs in the upstream manufacturing process since the obligation for the end-of-life management of the equipment rests on them. There are various approaches to EPR where a product take-back can be either be regulatory or voluntary and can be enabled through different administrative (recovery obligation, emission limits and landfill bans), informative (awareness initiation, like environmental labelling and reports) and economic (product taxes, advance recycling fees and virgin material taxes) instruments (Nnorom and Osibanjo 2007). In practice, mandatory EPR programmes are expected to yield better results since waste management is expensive and are therefore usually avoided. EPR should take care of the overall volume of waste by preventing and reducing waste, incorporating environmentally benign materials and designs in production, promoting use of reusable and recyclable materials and minimizing natural resource extraction.

EPR is mandated in the EU through the WEEE (Waste from EEE) Directive which aims at internalizing the environmental cost in product prices by requiring producers to take back their products at their end-of-life. The WEEE was adopted by the EU Parliament in May 2001. Additionally, to phase out the use of hazardous substances in EEE production by 2008, another directive, namely the Restrictions on Hazardous Substances have been passed in Europe. This can go a long way in controlling hazardous materials in recycled items (Terazono et al. 2006). Japan[7] has mandated take-back programmes and upstream design conditions (BAN/SVTC 2002). Many developing countries have also reproduced forms of EPR in their country to successfully guide the environment friendly management of e-waste. China, South Korea and Taiwan, through different national legislations, have obligated manufacturers, distributors and retailers to undertake the reuse, disassembly or disposal of e-waste themselves or pay fees to recycling management bodies to do so. However, the countries noteworthy in their lack of any e-waste legislation despite being big Asians hubs for recycling are India, Cambodia and Malaysia.

Though EPR has received much attention in international political circles, it is not without detractors. If production determines responsibility then since Asia has emerged as an important computer manufacturing region, it should shoulder its share of take-back (Iles 2004). But in reality these Asian companies often work as subcontractors to giant multinationals and tackle only a small component of the product for them. In such cases, the division of responsibility between the different subcontractors supplying a mother manufacturing company is a complicated issue. The greater the number of players in the production (or in recycling) business, the more difficult it is to assign responsibility to any of them (Terazono et al. 2006).

Explaining the transboundary movement of e-waste

Despite international, regional and national efforts to arrest the flow of e-waste from the global north to the south, the transfer of scrap materials not only continues but keeps growing steadily. To discern the reasons behind this persistent and increasing transnational movement, a political economy approach is adopted to locate the environmental degradation resulting from informal e-waste recycling in the broader social, political and historical context of capitalism. The rationale behind this waste transfer from the formal sector of production and consumption to the informal sector of recycling can be categorized as described below.

Economic factors

It is simple economic logic that guides the scrap trade to developing countries. Complicated EEE demands manual dissembling processes to remove the valuable parts from the trash in a cost-effective manner. Hence, the ready availability of cheap labour is a prerequisite for the labour-intensive dismantling or recycling of such products (Iles 2004). Moreover, the numerous kinds of such gadgets flooding the market constitute a real hurdle for the development of any standardized method of automated recycling (Iles 2004). In developing economies with inadequate employment opportunities and deeply entrenched poverty there is always a pool of unemployed labourers who are willing to work at a minimum wage or even lower. In the USA the cost of formally recycling a home computer is US$20 while it is only US$4 in informal recycling in India (Gattuso 2005). Moreover, EEEs typically contain precious metals like gold, silver, platinum and copper, which have a high resale value and thus earn lucrative returns (Sinha-Khetriwal et al. 2005). Hence it provides a profitable business option in developing countries and there is seldom a dearth of interested scrap dealers, waste traders and big recyclers who find e-waste dumping rewarding.

Institutional factors

Nationally, different institutional restrictions on e-waste management exist in developed and developing countries. Environmental regulations in the former are very strict and are relatively lax in the latter. Without an appropriate institutional infrastructure, the regulatory frameworks that are in place in industrializing countries are not duly enforced (Widmer et al. 2005). To hide the occupational and health hazards from concerned authorities, the main site of e-waste recycling or disposal is the informal sector, where cheap labour is commonly available, in countries where the sustainable management of e-waste is not practised. As the environmental regulations become more stringent in the developed nations, the volume of e-waste shipped off-shore illegally increases. Gattuso (2005) have argued that as a result of the imposition of a ban on desktops from municipal landfills in the USA, the export of this scrap has increased to countries where there is no such ban. Thus the so-called recyclers in the USA in reality act as scrap brokers, since actual e-waste management proves to be an expensive operation in which they are forced to abide by prevailing environmental standards.

Technological factors

The scrap trade is often rationalized in the name of transferring advanced knowledge to the industrializing world. Many contend that this would bridge the digital gap by bringing in the fruits of sophisticated technology that can be imitated and learned from. Through recycling technologically superior products, the industrializing countries would eventually adopt an appropriately technical route to industrialization and development. Furthermore, using second-hand items that have been discarded in developed economies would provide inexpensive opportunities via secondary resale markets (Agarwal et al. 2003) to those who would have otherwise been deprived from using them. Primarily computers that are deemed to be obsolete due to rapid technological improvements in the global North can contribute to digital learning for poorer communities worldwide. As donations and charity items, thousands of computers are shipped to schools in rural areas in developing countries to impart electronic education to underprivileged children. Reuse is ideally an environmentally friendly concept, but the items designated for reuse very soon reach their end-of-life and their addition to waste is merely postponed for a short period (Puckett and Smith 2002). Moreover, second-hand items are rarely tested for functionality and often completely junk devices find their way to developing nations (Nnorom and Osibanjo 2007) using the loopholes created by many governments who criminalize the dumping of scrap but not that of secondary goods.

Environmental factors

In 1991 the then Chief Economist of the World Bank, Larry Summers, in an internal memo, justified the Bank's motivation behind encouraging the migration of dirty industries to the less developed countries (Boyce et al. 2007; Vallette 1999). Widmer et al. (2005) summarize Summers' logic for dumping toxic waste as claiming that the less developed countries lose least productivity from increased morbidity and mortality; that they have enough clean air and water to afford pollution trading schemes and that they are unable to afford environmental protection, which is a luxury of the rich.

Even if one does not endorse this extreme view, it is true that the concern for a certain standard of environmental quality is believed to be a concern of the affluent: poor people, who are worried about getting their daily bread, cannot afford it. Ingelhart's post-materialist thesis (1997) puts forward a similar idea. Based on the experience in industrialized nations, the thesis postulates there is a shift from materialist to post-materialist values in which the concern for a standard environmental quality arises only when people's basic economic needs have been met (Martinez-Alier 1995).

Notwithstanding the reasons, the fact remains that much of the developed nations' WEEE ends up in the developing economies of the world. To escape the scrap trade watchdogs, waste is persistently exported in the guise of products. In the EU, trade in products is not covered under the Waste Shipment Regulation and following the definition of product[8] provided by General Product Safety Directive 2001/95/EC, EEE 'for reuse without prior refurbishment' is exempted from the Regulation (Maxianova 2008). This loophole is regularly exploited by companies transporting WEEE away from the developed countries, leading to a skewed environmental burden on poor communities that process toxic e-waste without any protection and rights.

Environmental injustice in e-waste streams

The disproportionate weight of environmental problems borne by marginalized and the disenfranchized individuals constitutes a gross violation of the principles of global environmental justice (EJ). Since its conceptualization in the USA in the 1980s, the notion of EJ has attracted weighty scholarship and strong endorsement. The differential environmental outcome for specific underprivileged groups constitutes an infringement of their human rights. The right to a clean and safe environment has been enshrined in the Rio Earth Summit (UN Convention) in 1992 (Cutter 1995).

The term EJ can have different connotations and interpretations for different groups of people (Capek 1993). But the basic idea of EJ is to ensure the equitable spatial distribution of environmental risks irrespective of race (around which it was first envisioned), class, nationality, ethnicity, gender or any other discriminating factor. Historically, some communities have often shouldered an unequal burden as a result of discriminatory societal power structures or prejudiced institutional mechanisms. These mechanisms can also lead to the formulation of policies that favour the powerful elite at the expense of vulnerable groups. EJ calls for a balance in the share of environmental benefits and costs on different sections of the community over time and space, as it has been shown that the poor, minorities, the socioeconomically weak and the powerless have been traditionally exposed to greater environmental hazards. They have also been systematically excluded from democratic participation by being relegated to the margins of important environmental policies and decisions (Adeola 2000). Built from the grass-roots struggles of local and indigenous communities in search of environmental equity, the EJ movement has defied the notion that impoverished people cannot demand an improved quality of life and a healthy environment. Instead of the lofty and elite "white upper-class environmental rhetoric" (Cutter 1995), it has brought to the fore the people whose lives and livelihoods are directly impacted upon by environmental degradation.

In the international waste regime, environmental injustice is inflicted at a different spatial scale onto the disadvantaged groups in the less developed nations by the transnational dumping of WEEE. Iles (2004) highlights the political dynamics behind the production and consumption of risk that might negatively influence everyone and not just those who are typically deprived. Hence, he appeals for a systemic precautionary approach starting right from the stage of design and manufacture, which encompasses the whole life cycle of these products and not just the technical end-of-pipe solutions like waste treatment (Iles 2004). The distributional discrimination in e-waste is not limited to a North–South phenomenon. It can also be prevalent within the geographical confines of a nation. For instance, in California prison workers are exploited by the recycling companies (in alliance with the state) without benefits and earning wages as low as 26 cents per hour (Puckett and Smith 2002). In terms of the dependency framework we can see this as the creation of core and periphery like-situations within the same society where the periphery bears the brunt of the impact of poor health and a polluted environment (Adeola 2000). Thus, it can be observed that while the formal sector enjoys the fruits of electronic and electrical production and consumption, disadvantaged workers in marginalized conditions are left with the job of cleaning up the waste. These workers can be located in the global South or in industrializing economies or even in deprived areas of an developed country – often in the informal segment of the economy. And, as e-waste keeps expanding, such sections of the society everywhere increasingly face environmental injustice.

Capitalism and informalization of e-waste

Though much emphasis has been given to the transboundary flow of e-waste and the resultant environmental injustice meted out to marginalized populations of waste workers (largely operating in the informal economy), there has been hardly any attempt to connect this phenomenon with the overarching framework of capitalism. The unsustainable nature of capitalist production and its socioeconomic organization is exposed in the colossal creation of waste. Some of the recent trends in capitalism have further accelerated waste generation.

Consumerism

In the current era of global competition, a steady flow of profit for the expansion of capitalism is orchestrated by the upsurge of consumerism. A throwaway consumerist culture is methodically created through marketing strategies and advertisements to ensure the never-ending desire for commodities. Mountains of waste result from this insatiable desire to own more and better, newer, trendier goods. Fast progress in technology, particularly in the field of information and communication, has aggravated this further. An abundance of novel models, cheaper gadgets and superior digital products are flooding the market every day to lure consumers into purchasing the very latest. The average life span of a computer was reduced from six years in 1997 to less than two years in 2005 (Oteng-Ababio 2010). Another significant factor behind this artificially constructed need for possessions is the planned obsolescence of hi-tech EEE. This is in total contradiction to the needs of the hour, which is to minimize waste and organize appropriate management and disposal methods (Soper 2003).

The pattern of consumerism is reminiscent of Thorstein Veblen's conspicuous consumption (*The Theory of the Leisure Class* 1899) where to display social status and wealth, individuals indulge in extravagant spending on goods and services. There is econometric proof to support Veblen's thesis in the contemporary era (Bagwell and Bernheim 1996). The market for EEE items and other luxury items thrives on the prestige and status people associate with the ownership (preferably exclusive) of the goods. Such a consumption-oriented society can only be maintained by the continuous appropriation of nature. Consequently, there is escalating natural resource extraction and depletion putting severe pressure on sustainability.

Urbanization

Globalization has brought in new forms of inequality through uneven development in urban and rural settlements. To reap the fruits of globalization along with rapid industrialization and modernization, more and more people migrate to the cities or at least to the suburbs. This has ushered in the phenomenon of uncontrollable urbanization in the system. Almost half the world's population, or three billion people, live in urban centres (Cohen 2006). A rising population with growing income and changing lifestyles promotes the culture of consumerism. An urban life is typically characterized by heightened consumption and wasteful attitudes. It has been observed that the question of solid waste management confronts every big and emerging city in the world. In China the annual volume of municipal waste has assumed the proportions of a crisis (Suocheng et al. 2001). In Africa the proportion of e-waste is fast increasing and posing serious challenges to urban growth (Achankeng 2003) and sustainability. Hence, the altering trend in urban consumption habits causes environmental degradation.

The changing order of world capitalism and its various aspects have produced an unprecedented volume of waste, which carried severe consequences for environmental sustainability. This remains largely hidden from the public eye through the informalization of waste management. Informalization can be understood as a movement towards economic activities that fall outside the formal economy and the formal regulatory environment (Chen 2007). It denotes a process of change in the organization of work and employment relations in favour of fluidity and deregulation, resulting in what is popularly known as the informal economy.

In the case of WEEE, the scrap traffic brings about this informalization by shifting the weight and repercussions of e-waste processing onto the informal sector, away from the eye of the regulating authorities. Thus the 'second contradiction of capitalism' (O'Connor, 1994, 1998)[9] is manifested in this act of informalization of e-waste whereby toxic rubbish is often illegally dumped (Network, 1989) at a huge social and environmental cost to the informal waste-worker. Rather than investing in suitable recycling infrastructure (Puckett and Smith 2002), the WEEE is channelled to places where it is handled, segregated and managed at very low cost by socioeconomically impoverished individuals who are restricted in their choice of a livelihood. This is achieved through the deliberate act of the spatial shifting of e-waste to the informal processing sector. Recycling units in the developed countries are formally owned and require huge capital investment. Thus by passing the e-waste on to the informal sector in the global South, the system saves significantly on waste recycling. The surplus thus accumulated feeds the expansion of the capitalist system, making informalization an essential tendency of capitalism that is encouraged to augment and reproduce the order.

Conclusion

In this chapter the way in which capitalism projects a sustainable front through a movement of environmentally harmful activities in the informal sector, as illustrated in the case of e-waste recycling, is established.

The resulting environmental and occupational dangers unleashed on impoverished people in the informal economy involves a gross violation of environmental equity and justice. Puckett and Smith (2002) have extensively documented the pollution in the e-waste processing centre in Guiyu, in the Guangdong Province of China, where most of the waste comes from North America, together with examples of European, Japanese and South Korean waste. India and Pakistan also receive substantial waste; Delhi is reported to be a major destination for recycling obsolete domestic computers and those imported illegally from other countries. If the recycling operations occur in their countries of origin they are obliged to to take place formally by abiding with all the statues laid out for environmental protection. But the absence of such strict institutional regulations and implementing mechanisms create an advantageous (read as cheap) incentive for the transfer or informalization of e-waste to developing countries. The issue of e-waste from this perspective warrants further research to discern the linkages between the different players associated with the scrap trade.

Notes

1. In this chapter "recent history" refers to the post-World War period of approximately 60 years.
2. Imposed through the structural adjustment programmes on developing countries (Gerry 1987).
3. Labour union activism also took a backseat due to the deregulation of the labour market (Gallin 2001).
4. Estimates from the recycling industry show that out of the total e-waste collected for recycling in the USA, 50–80 per cent is shipped abroad (BAN/SVTC 2002).
5. Apart from the USA, Afghanistan and Haiti have also signed but not ratified the Basel Convention.
6. The Organization of African Unity was established in 1963 to promote the unity and solidarity of independent African countries.
7. Under the Home Appliances Recycling Law enforced in 2001 in Japan, manufacturers and retailers are obliged to accept discarded common household appliances from consumers. The Law for Promotion of Effective Utilization of Resources mandates manufacturers to accept personal computers for recycling, the cost of which can be added to the product price (Terazono et al. 2006).
8. "This definition shall not apply to second-hand products supplied as antiques or as products to be repaired or reconditioned prior to being used, provided that the supplier clearly informs the person to whom he supplies the product to that effect". (Directive 2001/95/EC of the European Parliament, cited in Maxianova 2008)
9. According to O'Connor (1998), the second contradiction of capitalism is the destruction of nature and environment inflicted by the advance of the capitalist production and organization.

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Part III

E-waste and its environmental and health impacts

4

Environmental consequences of recovering valuable elements from electronic waste using crude methods in Aba, South-east Nigeria

Innocent C. Nnorom and Oladele Osibanjo

Introduction

Waste electrical and electronic equipment (WEEE) or electronic waste (e-waste) is the most rapidly growing waste problem in the world today (Osibanjo and Nnorom 2008; Osibanjo et al. 2008). It is a crisis, not only of quantity, but also one born from the content of hazardous material such as lead mercury, beryllium, cadmium and brominated flame retardants (BFRs) that pose both human and environmental health threats. Presently, large quantities of e-waste – illegally imported or generated locally – pose serious management challenges in Nigeria (Osibanjo and Nnorom, 2007, 2008; Osibanjo et al. 2008; Nnorom and Osibanjo, 2008a). This chapter presents information on the material flow of used EEE into Nigeria and the resulting pollution at a site used for the open burning of e-scrap to recover recyclables.

Dumping used electronic equipment in Nigeria

WEEE dumping statistics

A study by the Basel Action Network (Puckett 2004) revealed the magnitude of the transboundary movement of WEEE into Nigeria. An average of 500 containers enters Nigeria through the Lagos ports monthly, each containing about 800 computer monitors or central processing units. This

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Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
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indicates that an average of 400,000 second-hand or scrap PCs are imported per month through the Lagos ports alone. This amounts to an annual importation of an estimated 5 million PC units, with an estimated weight of 60,000 metric tons (Nnorom and Osibanjo, 2008a). Second-hand PCs and other categories of EEE are also imported through other seaports and airports and through donations by charities to organizations and educational institutions.

The BAN study observed that between 25 and 75 per cent of the imported second-hand computer goods (i.e. 60,000 tons) are unusable junk that are neither functional nor repairable (Puckett 2004). This amounts to an importation of 15,000–45,000 tons of scrap recyclable electronic components, which may contain as much as 3,600 tons of Pb. Assuming this trade continues unabated, at an annual increase of 10 per cent, then an estimated 40 million units of PCs or monitors (or 468,000 metric tons of e-scrap) would have been imported over the period 2005–2010 (Nnorom and Osibanjo 2008a). This will amount to an importation of about 40,000 metric tons of lead for the period under consideration, or 77,000 tons of e-scrap per year (Nnorom and Osibanjo 2008a).

Sources of the imported WEEE

From tags on the imported appliances and the information on the computer hard drives, the BAN study (Puckett, 2004) estimated that about 45 per cent of the WEEE imported into Nigeria are from the EU, 45 per cent from the USA and the remaining 10 per cent from other locations such as Japan, Israel, Korea and Singapore.

Transboundary movement of WEEE: an example of environmental injustice

Some developed countries reportedly export as much as 80 per cent of the WEEE collected for recycling (Antrekowitsch et al. 2006; Hicks et al. 2005; Puckett and Smith 2002). Kibert (2004) is of the view that "disposing of e-waste without any environmental controls is unethical, especially considering that consumers pay for this waste to be safely disposed of, not dumped on the ground of a developing country".

Theoretically, the reasons given for the transboundary movement of WEEE to developing countries are: (i) it will benefit those who are too poor to afford brand new equipment (thereby bridging the digital divide); (ii) it will lead to environmental gains and protection as the cheaper labour in the developing countries can make the repair and reuse of the old equipment feasible, giving it a longer life, or even recycle e-scrap; and, (iii) the reuse of second-hand devices will forestall the need for more products to be manufactured. However, it has become clear that there are other and more salient, reasons behind this environmental injustice: (i) the cost of recycling is higher in developed countries than in developing ones; as the cost to recycle a home computer in the USA is US$20 as against US$4 in developing countries such as India (Nnorom and Osibanjo 2008b), (ii) the developed countries are using legislation and regulation to discourage recycling within their borders to avert environmental pollution. The dumping of e-waste in developing countries is environmentally unjust and undermines the health of the ecosystem (Brigden et al. 2008). This exposes these countries to a toxic legacy forcing them to choose between "poverty and poison" (Puckett and Smith 2002). This is all the more so because of the lax enforcement of related regulations (where they exist) and because these countries do not use appropriate technology for waste management and adopt informal recycling, which is less profitable as well as unsustainable and environmentally hazardous (Brigden et al. 2008; Wong et al. 2007).

Management practices for end-of-life electronics in Nigeria

In Nigeria, there is virtually no capacity for formal recovery operations for e-waste materials, as a result of which these items are discarded in local dumps (Nnorom and Osibanjo 2008a; Osibanjo and Nnorom 2007; Puckett 2004). E-waste is disposed of in undesignated places or open dumps with municipal solid waste (MSW) (including in surface water and drains) or buried with MSW in unsanitary landfills (Figure 4.1). There is also the open burning of cables and selected components of e-waste to

Figure 4.1 E-waste disposal with municipal solid waste

Please see page 187 for a colour version of this figure.

Figure 4.2 Material recovery from selected components

Please see page 187 for a colour version of this figure.

recover valuables (Figure 4.2). The product is subsequently exported for refining. The reasons for the present management practices include the large in-flow of second-hand EEE (most of which is unusable), ignorance of the toxicity of e-waste, the absence of an infrastructure for formal recycling, the absence of legislation dealing specifically with e-waste and no effective take-back programmes.

Implications of present management practices

The implications of the present management practices include a loss of resources that could be recovered through formal recycling; energy wastage in producing new components and products; environmental pollution and health implications – the exposure of human and the ecology to toxins.

Experiment

Part of the results of our study of a site used for open burning of selected WEEE components to recover recyclables in Aba, South-eastern Nigeria, is presented here.

Description of sites studied and the recovery activities

Open burning of waste is a regular method of reducing the volume of waste in Nigeria before final disposal at unlined (unsanitary) landfills. The site studied is used for the open burning of electronic waste components for the recovery of the material in them. The site is surrounded by

Figure 4.3 Material recovery from selected components

Please see page 187 for a colour version of this figure.

residential buildings and is used regularly as a major thoroughfare. Interviews of individuals working at the site indicated that they are paid to collect certain components of the electronic waste, burn them and recover the copper, aluminium and other valuable materials. Routinely, copper wire is burnt to recover the wire (Figure 4.3). Sometimes, physical separation processes are adopted to recover the wires, in which case the cables are cut open to recover the copper cable inside. The recovered materials are transported to Lagos for export. Some recovered material is used locally. Workers at this site go round Aba city and other nearby towns to buy selected electronic products or components. They often engage waste collectors to supply the desired e-waste categories or components.

Sample collection and preservation

Surface soil samples and profile soils (the upper 0–100 cm) were collected at three different spots at the centre of the waste burning point and made into composites. The soil profile samples were collected at four different levels: 0–10 cm, 10–30 cm, 30–50 cm and 50–100 cm. Control samples were collected about 200 m from the site studied. There was no visible e-waste disposal activity at the control site. The collected samples were stored in polyethylene bags, labelled on site and transported to the laboratory. Scrap metal, debris, stones and wood were manually removed from the soil samples. The samples were air-dried for 5 days and stored in the laboratory prior to the next analytical procedure. Prior to analysis, the soil samples were dried in a moisture-extraction oven at 105°C to constant weight. Plants growing at the site were also collected and analysed for contamination by heavy metals.

Sample preparation

Soil samples digestion. The soil samples were digested using a 1:1 mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$). Then 5 mL of the acid mixture was added to the sample in a digestion flask and heated to 120°C in a digestion hot plate until the evolution of white fumes.

Sequential extraction study. The reactivity and potential bioavailability of heavy metals increase with increasing solubility (Wong et al. 2007). For example, soils with a large proportion of heavy metals in exchangeable fractions are potentially more hazardous than soils in which the heavy metals primarily reside in the residual fraction (Chen et al. 2003). The sequential extraction schemes proposed by Tessier et al. (1979) have been in use for speciation studies. Modified versions of this method are also in use (Gupta and Sinha 2006; Lu et al. 2003; Sutherland and Tack 2003). All the soil samples studied were made into a composite, which was subsequently used in the sequential extraction studies. The method by Lu et al. (2003) was adopted in the separation of the heavy metals into five fractions: exchangeable (F1); carbonate (F2); Fe and Mn oxides (F3); organic (F4) and the residue fractions (F5). The total metal content of the soil samples was determined after digestion with a mixture of HNO_3 and HF-$HClO_4$.

Preparation of plant materials. A local tomato species (*Lycopersicon esculentum*) growing near the site was collected and the plant parts (leaves, stem and root) studied for contamination by heavy metals (Ryan et al. 2001). The plant samples were weighed and ashed at 550°C and the ash subsequently treated with 2 M hydrochloric acid. All sample digests were analysed for heavy metals using a Buck Scientific atomic absorption spectrometer.

Results and discussion

Heavy metal concentrations in soils

The results indicate heavy contamination of the upper 100 cm soil profile. The mean lead and copper concentrations are 411 ± 1.1 mg/kg (range 410–413 mg/kg) and 3340 ± 905 mg/kg (range 2145–4299 mg/kg), respectively. The variations in copper and lead concentrations in the samples are presented in Figure 4.4 and Figure 4.5, respectively. The results of this study show the EU regulatory limits were exceeded for copper (50–140 mg/kg) and lead (50–300 mg/kg) in agricultural soils. The lead concentrations also exceeded the United States Environmental Protection Agency (USEPA) critical limit for lead in soils (400 mg/kg). No defined

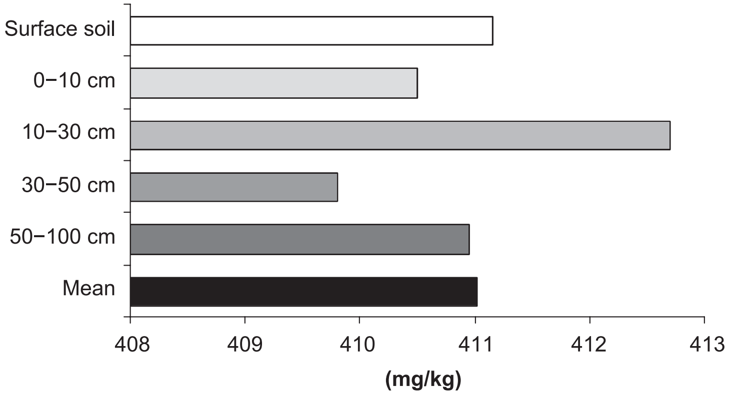

Figure 4.4 Copper concentrations in soils from e-waste recovery site in Aba, Nigeria

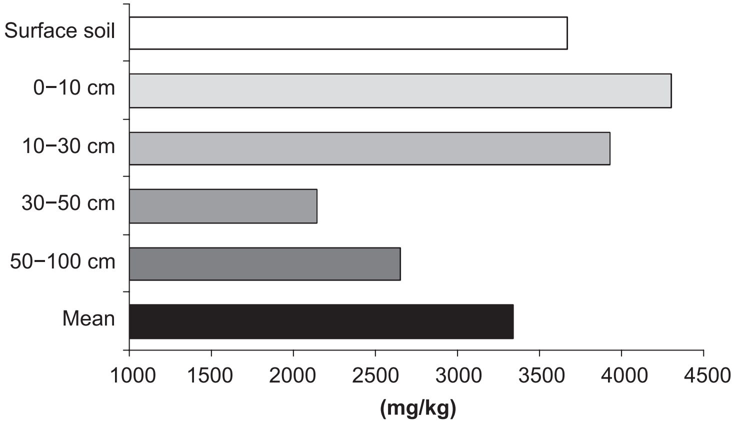

Figure 4.5 Lead concentrations in soils from e-waste recovery site in Aba, Nigeria

pattern was observed in the lead and copper concentration of the soil samples. Low metal concentrations in the controls (copper 9.6 ± 4.2 mg/kg and lead 22.1 ± 10.9 mg/kg) implicates e-waste recovery activities as the source of pollution.

Result of sequential extraction study

The results of the speciation studies expressed as percentages of the sum of individual fractions are presented in Figure 4.6. It shows that 84.74 per cent of lead and 91.36 per cent of copper reside in the residual fraction.

Lu et al. (2003) observed that the residual fraction of copper and lead accounts for 93.03 and 82.48 per cent, respectively, of the metals in non-urban soils.

The recovery of the heavy metals during the sequential extraction procedure can be judged by comparing the sum of each fraction with the total heavy metal concentration (Lu et al. 2003). The sum of the metal extracted in the five steps was compared with the total metal concentration. This comparison was in good agreement and the calculated mean recovery for the metals was 104.3 per cent. Lu et al. (2003) reported a recovery of 81.1–118.9 per cent. The results of the sequential extraction study showed metal speciation in this order: residual fraction (87.4) > organic-bound (4.93) > Fe and Mn oxide (4.79%) > carbonate (3.35%) > exchangeable (2.19%) for lead. The order for copper is: residual fraction (91.4%) > organic-bound (4.49%) > Fe and Mn oxide (1.64%) = exchangeable (1.64%) > carbonate (0.88%). These results indicate that the metals are not readily mobile. Lu et al. (2003) reported a similar relationship for lead and copper in their studies. The average distribution of lead and copper in the soils is residual fraction (88.05 ± 4.68%) > organic-bound (4.71 ± 0.31%) > Fe-Mn oxide (3.22 ± 2.23%) > carbonate (2.12 ± 1.75%) > exchangeable (1.92 ± 0.38%).

The sequential extraction scheme indicates that the exchangeable fraction is the first to be brought into solution and is considered to be easily available for plant uptake, while the carbonate fraction is susceptible to

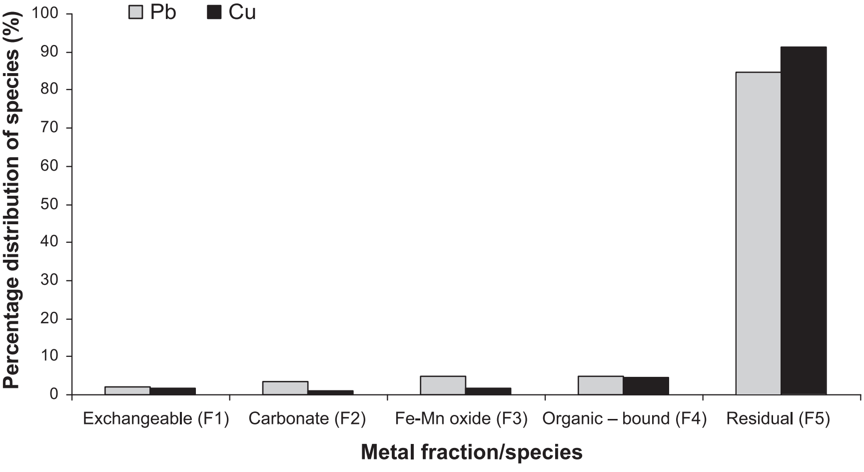

Figure 4.6 Distribution of fractions of lead and copper in soils from e-waste recovery site in Aba, Nigeria

pH changes. The Fe and Mn oxide fraction is unstable under low pH conditions while the organic fraction could be degraded under oxidizing conditions. The residual fraction is not considered to create a bioavailable pool since it is not expected to be solubilized over a reasonable period of time under natural conditions (Tessier et al. 1979). The amounts of non-residual fractions represent the amounts of active heavy metals. The mean non-residual fraction for the metals is 11.97 per cent. This is comparable to the values reported by Lu et al. (2003) (the non-residual fraction for copper, zinc (zinc), lead and chromium (Cr) in non-urban soils average 6.7 and 16.5%, respectively). Only very small amounts of copper and lead are present in the exchangeable fraction. Most of the metals are present in the residual fraction.

The results of this study show that a minimal percentage of the metals are in the exchangeable fraction. However, considering the high levels of lead and copper contamination at the site, the approximately mean 2 per cent of metal in the exchangeable fraction (F1) would give large concentrations of these metals in bioavailable forms. For instance, the 2 per cent of metal in the exchangeable fraction indicates that 66.8 mg lead per kg and 8.2 mg copper per kg are readily bioavailable. The non-residual fraction or active metal concentrations are 49.3 mg copper per kg and 400 mg lead per kg.

Contamination of plants

The results of copper and lead concentrations in the leaves, stem and root of the tomato *(L. esculentum)* are presented in Figures 4.7 and 4.8, respectively. The lead concentrations in the plant materials range from 1.1 ± 0.2 to 4.23 ± 0.45 mg/kg. The plant materials studied may constitute a source of lead intake if they are consumed as a vegetable. In light of the FAO/WHO guideline of an upper limit of 0.1–0.3 mg/kg of lead in edible vegetables (FAO/WHO 2000; Pasquini 2006; Tessier et al. 1979), the lead contents of some of the plant materials are up to 14 times the upper critical limit of this standard.

Plants are important components of ecosystems as they transfer elements from abiotic into biotic environments. The primary sources of elements from the environment to plants are air, water and the soil. The bioavailability of elements to plants is controlled by many factors associated with soil and climatic conditions, the plant genotype and its agronomic management, including active and passive transfer processes, sequestration and speciation, redox states, the type of plant root system and the response of the plants to elements in relation to seasonal cycles (Chojnacka et al. 2005). Our results indicate that the plants are exposed to heavy metals through their roots and leaves.

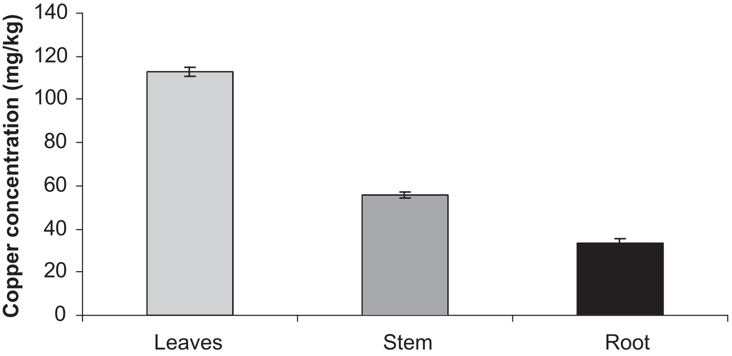

Figure 4.7 Copper concentrations in leaves, stem and root of tomatoes collected at e-waste recovery site

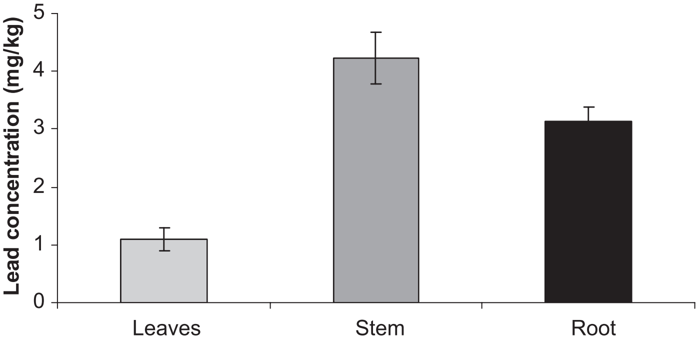

Figure 4.8 Lead concentrations in leaves, stem and root of tomatoes collected at e-waste recovery site

Discussion

The open burning of e-waste releases heavy metal-laden particulates into the air as such sites are often smouldering with thick smoke. There is the likelihood of human exposure by inhaling air contaminated by heavy–metal-laden particulates. For example, air samples with aerodynamic diameter smaller than 2.5 mm (particulate matter 2.5) collected at Guiyu, an e-waste recycling site in south-east China, showed concentrations of Cr, copper and zinc in PM 2.5 which were 4–33 times higher than in other Asian countries (Chojnacka et al. 2005). Similarly, the monthly concentration of the sum of 22 polybrominated diphenyl ether congeners contained in PM 2.5 of air samples at Guiyu were 100 times higher than in published data (Wong et al. 2007).

In Nigeria town refuse ash is regularly used as plant nutrient (fertilizer) in urban agriculture (Pasquini 2006). The ingestion of food crops (especially corn and vegetables) grown at such heavy–metal-laden sites (which may bio-accumulate such metals) could expose residents to toxins. Although epidemiological data is lacking in Nigeria, the information from other countries suggest that the consumption of such crops could have adverse effects on human health. Studies have shown that the residents in Guiyu had a high incidence of skin damage, headache, vertigo, nausea, chronic gastritis and gastric and duodenal ulcers, all of which may be caused by the primitive recycling processing of e-waste (Denga et al. 2006).

Children living or playing in such contaminated environments, including children engaged in scavenging at waste dumps would be exposed to these metals by inhaling them and through hand-to-mouth activities. Studies in China have shown that children living in e-waste recycling environments (like Guiyu, a town in China known for its crude e-waste recycling) have significantly higher levels of blood lead than children living in other towns (Huo et al. 2007; Zheng et al. 2008). Heavy metal contamination of plants and storm-water runoff has health implications for livestock and humans at the top of the food chain. Exposure routes include inhalation, dermal contact and ingestion, especially in children because of their hand-to-mouth behaviour. Soil heavy metal pollution is a serious problem worldwide and can be potentially harmful to human health via the food chain. Pb, a common pollutant, is of concern because it is not a plant nutrient but is potentially toxic to animals and humans. According to USEPA (1996), remediation is usually required when total soil lead exceeds 300–500 mg/kg or when extractable lead exceeds 5 mg/L. Heavy metals enter biological systems via food, water, air and the soil. The high levels of heavy metals observed in soils at the Aba e-waste recovery site have serious health implications with respect to the leaching of the heavy metals into surface and groundwater and the uptake of such metals by plants. Burning waste plastic materials such as BFR-containing materials and polyvinyl chloride could result in the emissions of high levels of brominated and chlorinated dioxins and furans that are known to be highly toxic. The open burning activity would also result in the release of particulates heavily contaminated with heavy metals and other toxic organic materials. These particulates could expose nearby residents and passers-by to toxins through inhalation.

Conclusion

The present material recovery activities at Aba have resulted in severe heavy metal contamination of the soil. There is a possibility for rainwater leaching these heavy metals into surface waters used for domestic purposes. This has serious health implications for communities that rely on such water bodies for drinking and other domestic uses. Furthermore, groups who are exposed in this way are generally poor and may have their poverty worsened due to the adverse health consequences of the consumption of food and water contaminated with heavy metals. Metal pollution at the site studied also creates the potential for the contamination of groundwater as well as crops in nearby farms. The metal concentrations found in this study largely exceeded those measured in natural unpolluted Nigerian soils, and exceeded regulatory threshold limits for metal in soils, thereby confirming the existence of metal pollution, which resulted from the e-waste material recovery activities, at these sites.

The implementation of an integrated management approach for e-waste requires the Nigerian government to look at e-waste from two perspectives: as a source of pollution requiring a hazardous waste management strategy (the ecological perspective), and as a potential source of recoverable resources (the economic perspective) (Osibanjo et al. 2008). The harmonization of these issues will help in the development of policy instruments for the effective management of e-waste. This will entail the introduction of formal recycling, energy recovery from waste plastics and the disposal of non-reusable items and residues using appropriate technology (Nnorom and Osibanjo 2009). The recovery of precious metals and copper and energy recovery from waste plastics are options in the eco-efficient management of e-waste. These options offer both economic and ecological gains (Osibanjo et al. 2008). The introduction of national policy and legislation dealing specifically with e-waste and the confirmation of the functionality of second-hand EEE prior to importation are some of the options available to the government in dealing with this difficult issue.

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5

Comparison of lead and copper concentrations in different parts of electronic computer waste imported into Nigeria

Kehinde Olubanjo, Oladele Osibanjo and Kike Oloruntoba

Introduction

The electronics and information technology industry is the world's largest and fastest growing manufacturing industry. As a consequence of this remarkable growth, combined with the phenomenon of rapid product obsolescence, discarded electronic equipment or e-waste is now recognized as the fastest growing waste stream in the industrialized world. Electronic devices and products contain an array of heavy metals such as mercury, lead, gallium, selenium, arsenic, zinc, cobalt, tin, palladium and aluminium (Puckett and Smith, 2002).

At the initial stages of design and development in the electronic industry, little consideration was given to long-term waste and the environmental impact of the products or of the hazardous waste stream generated during the industrial production cycle.

Though technologies for the production of electronic devices are being improved every day in order to replace the very toxic, persistent and bio-accumulative heavy metals, the fact remains that the materials that are replacing them are still heavy metals that are toxic to plants, animals and even humans.

The components to be examined in this chapter have been chosen because they are known to consist of heavy metals such as copper, lead, cadmium which when are very hazardous to humans, bio-accumulate and have carcinogenic properties. The cathode ray tubes (CRTs) in computer monitors and TVs contain about 8 per cent lead by weight (Smith et al.

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1996). They also contain small amounts of other toxic substances including barium, cadmium, chromium, copper and zinc (Lee and Hsi 2002).

Due to the lack of financial resources available to most people in developing countries, much of the growth in the information technology sectors in developing countries like Nigeria has been fuelled by the importation of used hand-me-down equipment and non-usable electronic scrap from rich developed countries (Grossman 2006).

Management of e-waste

The management of hazardous waste remains a central environmental issue internationally. This is clearly indicated by the existence of international conventions to regulate the movement of hazardous waste. The convention on the control of transboundary movement and disposal of hazardous waste on 22 March 1989, also known as the Basel Convention, was initiated in response to numerous international scandals regarding hazardous waste trafficking in the late 1980s (BAN 2007). The convention on the ban of imports into Africa and the control of the transboundary movement and management of hazardous waste within Africa or the Bamako Convention (1991), in turn places a total ban on the import of hazardous waste to signatory countries.

E-waste is usually disposed of in a variety of ways, including landfilling, recycling, incinerating and reusing. A landfill is a disposal area where e-waste is piled up and eventually covered with soil. The leaching of harmful chemicals and toxic metals from this site leads to groundwater contamination.

Environmental impacts of e-waste

The physiological and health impacts of toxic e-waste substances found in dangerous concentrations in humans and animals have been discussed by various researchers (Brigden et al. 2005; Environment Victoria 2005). In particular, they highlight the following findings:

- They disrupt endocrine systems including the oestrogen, androgen, thyroid hormone, retinoid and corticosteroid systems, inhibits the human androgen hormone reception and its ability to mimic natural oestrogen hormones, leading to altered sexual development in some organisms.
- They damage both male and female reproductive systems, interfering with the development of the testes, a reduction in semen production and quality, abnormal sperm morphology, low egg hatchability and reduced fertility rates.

- They cause DNA damage in lymphocytes, foetal and developmental toxicity, growth retardation and abnormal brain development, which can result in intellectual impairment and possible long-term impacts on memory, learning and behaviour.
- They damage the central nervous system and blood system, leading to depression and neurotoxicity, immune system suppression and the inhibition of a key blood cell enzyme.
- They damage the brain, causing swelling; the liver, inducing liver necrosis; the kidneys, including renal toxicity; the thyroid; pancreas; lymph nodes; spleen and bone, including bone toxicity.
- They lead to hypertension, cardiovascular and heart disease and respiratory tract irritation, including irritation of the nose, mouth and eyes.
- They cause vomiting, headaches, dizziness and nausea.
- They cause contact dermatitis, skin lesions, carcinogenic, including tumour promotion and lung cancer; anaemia; corticobasal degeneration (a currently incurable, debilitating disease that can sometimes be fatal) and mortality.

Some examples of sources of e-waste constituents and their related health effects are listed in Table 5.1.

Table 5.1 E-waste sources and their health effects (Source: Boralkar 2006)

E-waste sources	Constituents	Health effects
Printed circuit boards and computer monitors	Lead	Damage the nervous system, circulatory system, and kidney and affect brain development in children
Chip resistors and semiconductors	Cadmium	Neural damage
Relays, switches and printed circuit boards	Mercury	Chronic damage to the brain; respiratory and skin disorders
Galvanized steels plates and decorator or hardener for steel housing	Chromium	Bronchitis
Cabling and computer housing	Plastics and PVC	Affect reproductive system and immune system, and lead to hormonal disorders
Electronic equipment and circuit boards	Brominated flame retardants	Disrupt endocrine system functions
Front panels of CRTs	Barium, phosphor and heavy metals	Cause muscle weakness and damage to heart, liver and spleen
Motherboard	Beryllium	Carcinogenic in nature, causing skin diseases

The transfer of the end-of-life problems of e-waste to developing countries

The current export of e-waste from developed countries to developing countries for processing is detailed by Puckett et al. (2005). Rather than having to face the problem squarely, the USA and other rich economies that use most of the world's electronic products and generate most of the e-waste have made use of a convenient, and until now, hidden escape valve – exporting the e-waste crisis to the developing countries of Asia and Africa. Indeed, informed recycling industry sources estimate that between 50 and 80 per cent of the e-waste collected for recycling in the western USA are not recycled domestically, but instead it is rapidly placed on container ships bound for destinations like Nigeria and China.

Although a sizeable portion of the imported equipment is bought and refurbished by the electronic repair shops, what cannot be repaired serves as scrap, where the useful components are removed and used to fix other equipment. A lot of this equipment cannot be re-used and ends up on the landfills, thereby adding to the volume of the e-waste generated locally. In Nigeria, between only 25–75 per cent of the imported computer component can be cost-effectively repaired and sold, and much of the remainder is dumped or burned (Puckett et al. 2005). According to the Basel Action Network (BAN), in its media release version of (Gutierrez, 2005), a lot of this equipment is being sent to developing nations under the pretext of "building bridges over the digital divide". In this report the article concludes that three-quarters of the supposedly reusable electronics shipped to Africa's largest port are broken. One of the problems is that no one certifies whether or not the donated machines work before they hit the seas. Because of this, the report says, e-waste is a growing problem in Lagos and elsewhere in the developing world. Much of the waste ends up being discarded along rivers and roads. Often it is picked apart by destitute scavengers, who may face dangerous exposure to toxic chemicals in the broken equipment.

Although e-waste is a global issue, especially in most African countries where there is no effective management system, the truth of the matter is that Nigeria has remained a dumping ground for all kinds of computer scrap that comes into the country from industrialized nations, especially from European and Asian sources. Some of these products, according to findings, have been brought into the country by racketeers and non-governmental organizations (NGOs) as donations, which in the long term do not stand the test of time.

According to findings, even with the prohibition of international waste transfer by the Basel Convention, hundreds of containers stuffed with old computers and their accessories are shipped to Africa, including, Nigeria, where the demand is high among its large population. For instance, over a million computers enter Nigerian ports every month. These computers, according to investigations, are fraudulently shipped in most cases as reusable or refurbished goods.

Computer donations are just part of a large portion of unwanted electronic goods shipped to African nations every year from abroad. As the technology continues to develop at amazing speed, items nearing the end of their life span are being discarded for new, better and more fashionable ones. Most of these items have a short life span and will soon turn into e-waste containing deadly toxic substances. Because of the high cost of recycling these products, western economies prefer to avoid the economic implications of recycling some of these gadgets and Africa seems to be the most obvious destination for it. This practice, which continues unabated, worries the industry watchers and regulatory agencies, especially, the Standards Organisation of Nigeria, which appears to be unable to control the influx of these obsolete e-gadgets.

Materials and methods

Sample collection

The sample consisted of 59 used or faulty computers of different brands and types and from different manufacturers collected from different electronic repair workshops in Ibadan. Of the sample 35 were central processing units (CPUs) and 24 were monitors (see Table 5.2).

Sample preparation

The devices were dismantled individually and the components were classified into two major types:

- millable parts: printed wire boards (PWBs including chip container packages) in the CPU and monitor, (CRT)
- non-millable parts: metal frames, rods and other metal parts.

All the millable components were cut into small pieces and ground using a specially fabricated heavy duty mill in the the University of Ibadan Department of Mechanical Engineering, Faculty of Technology to achieve the desired particle size, and passed through a 2-mm mesh sieve. Wood chips were used to clean the milling apparatus and served as blanks to determine cross-contamination. The milled samples were thoroughly mixed to achieve homogeneity before removing aliquots for testing.

Table 5.2 Summary of computer components used for analysis

Product type	Manufacturer	Model no.	Serial no.	Year of manufacture	Weight of PWB device (g)
CPU	Unitech	N/A	M6309U0103138359	1999	536.2
CPU	QDI	N/A	D02040303501158	1998	581.4
CPU	ZP Com	6964B	989VE1150083	1998	543.9
CPU	Winbond	W83627F-AW	927S2C292113702	1998	476.2
CPU	V/N	VT82C686A	13C0N9800	1998	583.4
CPU	V/N	0102CG	10202400056	1999	538.2
CPU	Intel	L942TA86	FW82810DC100	1998	578.9
CPU	Intel	L8321L15	FW82371EB	1996	554.3
CPU	V/N	0107CD	13001901161	1998	531.5
CPU	V/N	JM 2023	2457600	2000	480.4
CPU	Intel	SL2VH	L006VA38	1998	514.0
CPU	V/N	694X	13B007600	1999	526.9
CPU	V/N	0051 CG	M630980101067465	1998	535.0
CPU	Intel	SL3P6	F9321J49	1998	538.7
CPU	V/N	0022CE	1EE0N2101	1998	567.8
CPU	Suma	MS7177CT	A30EE21501784		588.0
CPU	Unitech	0111CD	13B702200		542.2
CPU	Unisem	W29C020	9490I2939	1998	533.2
CPU	Cobra+1	6BXA-65A	N12811XN803999	2000	560.0
CPU	Ite	0016-CYS	IT8693F-A	2000	575.4
CPU	Qdi	PCI/PNP 686	249230652	1998	596.0
CPU	QDI	0360H	018196606	1998	557.1
CPU	V/N	0053 CD	0105550795	1999	593.2
CPU	Intel	CS4610-CM	ATAKL09729	1998	678.5
CPU	Winbond	W83977EF-AW	191483869	1998	608.5
CPU	Soyo	MC3240	272544304	1998	586.5
CPU	Winbond	9F002U-12B	GG201080001SA	1998	546.2
CPU	Winbond	SL2KK	FW82443LX	1995	484.2

CPU	Crystal	40-04831	CS4326B-KQ		625.2
CPU	Pro	MS6163	93692E29084970		579.1
CPU	V/N	0047CE	VT82C694X		502.2
CPU	Amibos	BR66096	827SC282126702SA	1995	568.5
CPU	Compaq	008313	332857-W1	1998	546.2
CPU	Pro	L1084S	204708433	1998	580.0
CPU	Chips	M9259	00115B3D742A		597.2
Monitor	Ultrascan	TM 4401	VP-N1B(Z)2080708		716.38
Monitor	Olivetti	N/A	2813773		461.34
Monitor	JVC	N/A	09568566		566.44
Monitor	Belinea	10 60 20	106020984125436	1998	884.06
Monitor	Ncr	B790	90-34021497	2000	608.73
Monitor	Blue Gate	TM-1550	2003080201804	2003	422.66
Monitor	New Diamond	8027554	N/A		590.55
Monitor	Samsung	551V	AN15HMDW800567V	2003	329.37
Monitor	Cheer	3DE	62-3VC-3DE2-E-76	2003	412.44
Monitor	Haisi	FH-568	MF53E031100107		563.63
Monitor	Nec Multisync 3v	JG-1535VMB	4401216TP	1991	801.87
Monitor	Proview	MD-848FGOE	FA BE5C43169		492.19
Monitor	Viewtec	M1454 A	4CPF13400623		644.62
Monitor	Komodo	H450	738 WK 002U02422	1997	642.71
Monitor	Philips	105S11/00	HD009947008417	1999	590.86
Monitor	Dell	D1025HE	66052-9-4X2F-97	1997	472.08
Monitor	Zinox	M553	131FNAC2002729	2001	507.24
Monitor	Ctx	1569ME	0H4-81200581	1998	505.02
Monitor	Reli Sys	TE 5559	JX92490225	1999	559.52
Monitor	Direct on PC 455	MH 455	MN43 E030612976		504.73
Monitor	Samtron	4 BI	HMBJ501273P	1998	403.73
Monitor	Acer	7234E	9174302003	2001	520.58
Monitor	Direct on PC 568	NH 568	MN53E030809252		578.92
Monitor	Nutech	N/A	0924	2002	507.05

Digestion of sample

One gram (1 g) of a representative subsample of the thoroughly mixed sample was weighed in a digestion vessel according to the Environmental Protection Agency (1966).

10 mL of 1:1 nitric acid (HNO_3) was added to the sample to make a slurry, which was mixed, covered with a watch glass and refluxed for 15 minutes and then allowed to cool. 5 mL of concentrated HNO_3 was added, and the solution was covered and refluxed for another 30 minutes. This was repeated for the sample until no brown fumes were given off, indicating the complete reaction with HNO_3. The sample was then heated at 95°C without boiling for 2 hours, maintaining a covering solution.

The sample was then cooled and 2 mL of deionized water and 3 mL of 30 per cent hydrogen peroxide (H_2O_2) were added. The vessel was covered with a watch glass, returned to the heat source for warming and to start the peroxide reaction.

Care was taken to ensure that losses did not occur due to excessively vigorous effervescence and less than a total of 10 mL of 30 per cent H_2O_2 was added until the general sample appearance remained unchanged. The sample was covered with a watch glass and heated at 95°C without boiling for 2 hours. After 2 hours, 10 mL concentrated hydrogen chloride was added to the digest, covered with a watch glass, and heated at 95°C for 15 minutes.

The digest was filtered through filter paper and the filtrate was collected in a 100-mL volumetric flask.

Results and discussion

The results show (see Table 5.3) that the lead and copper content in the PWB of the CPU in all samples exceed the threshold limits for these

Table 5.3 Summary of the range and mean (in parenthesis) of copper and lead concentration in the components analysed in mg/kg

Total threshold limit concentration	2500 (mg/kg)	1000 (mg/kg)
Component	Copper (mg/kg)	Lead (mg/kg)
PWB of CPU	83100–705300 (376195.7)	18060–400650 (89882.14)
PWB of monitor	39150–630300 (149818.8)	8460–80850 (47043.75)
CRT	73.2–468 (165.83)	429–9900 (4340.81)

metals by 400 and 282 times, respectively, while in the PWB of the monitors, the threshold limit was exceeded by 81 and 252 times, respectively. It was observed that the copper content in the CRT is far below the threshold limit in all the samples, while the lead content is very high in this part of machine, exceeding the regulatory limit by 10 times. PWBs contain 10–40 per cent copper by weight (Ernst et al. 2003), and this is line with the results obtained in our experiments, indicating a high level of copper in the PWB of the CPU and the monitor and a low level (far below the threshold limit) in the CRT.

A previous study of e-waste (Department of Toxic Substances Control 2004) reported that the copper and lead content exceed the total threshold limit concentration of both elements, although at a lower concentration than the average reported in the present study. This discrepancy is likely to be due to the fact that in the Department of Toxic Substances Control study the PWB was milled without any capacitor on it, but in the present study the capacitors were milled together with the PWB, which may account for the higher level of concentration reported in this study.

A comparison of the computer data used for this study and other e-waste analyses (Lincoln et al. 2007) indicates that the concentration of these two elements is above the regulatory limit, though for copper the concentration is lower (81 times) as compared to 282 times in the PWB of the CPU and 252 times in the PWB of the monitor in the present study. The lead concentration was found to be 10 times greater than the regulatory limit, which is the value obtained for lead in CRTs in the present study (Figure 5.1).

A comparison of the concentration of the two metals in the three parts analysed showed that copper has a higher concentration than lead in the PWB of the CPU and monitor while lead is more concentrated than copper in CRTs.

These data demonstrate that electronics manufacturers who seek to design products that are exempted from the current classification of hazardous waste will need to address not just lead (as the current wave of responses to European and Japanese regulations has shown) but, most importantly, the copper content too. However, extensive testing should precede the selection of alternative materials.

Recommendation

The disposal of e-waste, particularly computers, in Nigeria has become a serious problem since the methods of disposal are very rudimentary and pose grave environmental and health hazards. The situation is worsened as there are no e-waste management and disposal methods, because of

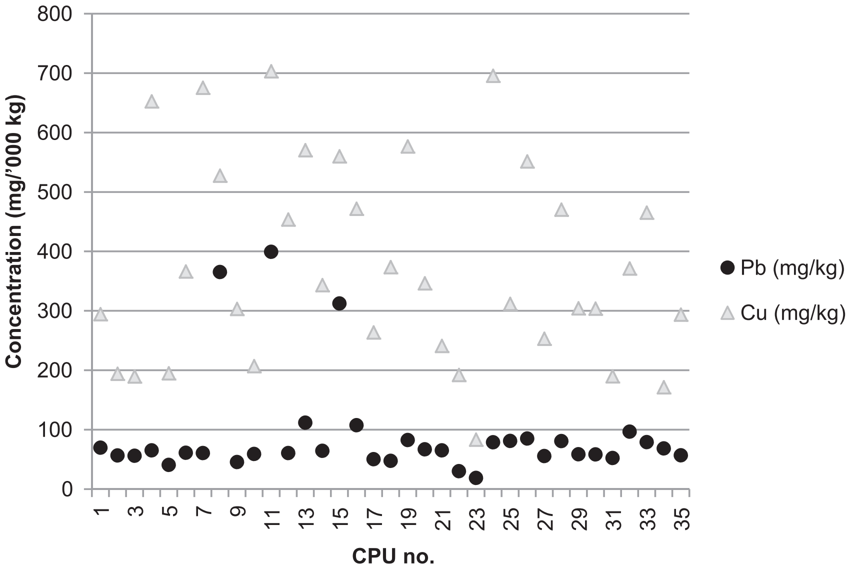

Figure 5.1 Total concentration of lead and copper in the printed wiring boards of different CPUs. Total threshold limit concentration of lead = 1000 mg/kg and of copper = 2500 mg/kg

factors such as poor awareness, inadequate legislation, lack of funds and reluctance on the part of governments and corporate organizations to address this critical issue.

A plan of action for the management of e-waste has to be implemented as a matter of urgency and the most important participants and stakeholders in the action plan should include:

- the media – for awareness and public education
- society – represented by NGOs and environmental activists
- corporate organizations – research and development teams
- government – policymakers

The success of any environmental policy depends on the sections of the population understanding the functioning of the environment and the problems poor management present. The implication of this is that environmental education should reach all sectors of the community. To this end, continuous and detailed education programmes should be implemented at all levels of the society so that every Nigerian becomes aware of the problem and fully assumes responsibility in safeguarding the environment. In the formal system, environmental education should be integrated in the school curriculum. In the non-formal system, sustained efforts should be made to promote awareness among policymakers to provide training for resource managers at appropriate levels and promote greater public awareness and motivation for environmental action plans.

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6

E-waste: Disposal behaviour of consumers in Nakuru municipality, Kenya

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Introduction

E-waste is a generic term embracing various forms of electric and electronic equipment nearing the end of their useful life or that have ceased to be of any use to their owners. E-waste is inevitable in contemporary society and is found everywhere. It has thus become an issue of global concern, due to its increasing volume and the fact that toxic substances that are present in it are non-biodegradable, the recycling methods that are used and the transfer of its end-of-life problems to developing countries (Vossenaar et al. 2006). The sheer volume of e-waste poses health problems to human and other organisms but more important is the problem posed by the compounds it is made from, referred to as persistent bio-accumulative and toxic chemicals (PBTs) (US Environmental Protection Agency [EPA] 2001). These compounds move easily between air, water and the soil and they can spread over large areas and do considerable, long-lasting damage to the environment. High concentrations of PBTs can accumulate in the fatty tissue of organisms exposed to them. As a result, humans are most likely to be exposed to these PBTs as a result of consuming animals that have been exposed to them.

PBTs are associated with a range of adverse human health effects, including damage to the nervous system, reproductive and developmental problems, as well as genetic impacts and cancer. Some of the PBTs found in cell phones and other electronic equipment include arsenic, antimony, beryllium, cadmium, copper, lead, nickel and zinc (Biddle 2000). A study

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Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
United Nations University Press, 2013, ISBN 978-92-808-8035-9

carried by Prather and Hsu (2008) found that a chemical used in making flat screen televisions and in liquid crystal displays contains nitrogen trifluoride (NF_3), which is a greenhouse gas 17,000 times more potent than carbon dioxide (CO_2). If this equipment is not properly disposed of, the release of NF_3 into the atmosphere may contribute to global warming. However, much of this equipment can be reused, refurbished or recycled in an environmentally sound manner so that it is less harmful to the ecosystem. Furthermore, some of the substances contained in these components are very valuable, for instance; some e-waste has a significantly higher concentration of metals like gold and copper compared to an equivalent weight of a typical ore (Biddle 2000).

In a bid to bridge the digital divide, developed countries donate old computers and other electronic equipment to Kenya and other developing countries through charitable organizations for reuse, while others dump obsolete equipment especially computers, for recycling (EMPA 2008). At the time of writing the Kenyan government has not put in place measures or policies to ensure that the electronic equipment that is imported or donated to institutions is not obsolete and is in good working condition.

The developing economy in Kenya has resulted in a rapid increase in the use of electronic equipment. Many Kenyans today have access to computer facilities at home, school and cyber cafés in business centres where they can access the internet. Many also have access to mobile phones and video and audio equipment, including MP3 players. A study carried out by the Kenya ICT Network estimates that about 3,000 tons of PCs and printers were discarded in the country in 2007 (Waema and Mureithi 2008). This implies that an increase in e-waste in Kenya is inevitable. This should raise concerns about future quantities of e-waste in the country. However, it is already a requirement of the Ministry of Information that discarded electronics are disposed of in an environmentally sound manner. Further, Kenya's regulator, the Communications Commission of Kenya, has included a clause in its unified licensing framework requiring licensed operators to take responsibility for the safe disposal of their own technology (UNEP 2008). This, then, should serve as a basis for shaping policy on the management of e-waste in Kenya.

Most schools and institutions of higher learning such as universities equip their computer laboratories with second-hand or refurbished computers. Some of these computers are already obsolete and are discarded without being put into any use. The result is that there is high amount of computers e-waste in the learning institutions in Kenya. Concern on the growing amount of computers e-waste has led to the initiation of an e-waste management plant that is located in Embakasi in Nairobi. This is a joint venture between Computers for Schools Kenya (CFSK) in collaboration with Nairobi City Council and the local Embakasi community. CFSK receives computers from charitable organizations and sells them to schools at a subsidized price. They are also mandated to service the computers they take to schools and replace obsolete computers or those that are not functioning. This activity has resulted in the accumulation of obsolete computers necessitating the opening of the recycling facility.

CFSK lacks the infrastructure to dispose of the hazardous portions of the e-waste produced, hence the facility in Embakasi only dismantles and separates the components in e-waste, where the metals are recycled locally. Motherboards are shipped to Asia and Europe for further processing and monitors, due to the toxicity of their components, are shipped to Norway for proper disposal. CFSK has been promoting local innovation by recycling cathode ray tube computer monitors and converting them to affordable TV sets (UNEP 2008). However, the Embakasi recycling facility lacks capacity and hence it deals with obsolete computers from schools within their jurisdiction. This is a clear indication that Kenya does not have adequate infrastructure to deal with the pre-processing of e-waste.

Nakuru municipality is a provincial headquarter serving as an administrative, industrial and commercial centre. It is also the fourth largest cosmopolitan town in Kenya, in which electronic equipment is increasing used, resulting in large amounts of e-waste. Obsolete computers are being stockpiled in institutions of learning, offices and electronic repair shops. There is no known e-waste recycling facility in the municipality. There is therefore a need to identify how the residents are disposing of their e-waste and learn whether they are aware of the effects of the poor disposal of e-waste on human health and the environment. The findings can be used in seeking interventions to curb exposure of humans and the environment to the hazardous components of e-waste.

Materials and methods

The study was carried out in Nakuru municipality in both its residential and central business district. The town is 160 km north-west of Nairobi. To the south of the municipality is Lake Nakuru National Park and to the north is the Menengai Crater. The main municipal dump site is located on a hill on the north-western side of Nakuru. Lake Nakuru is the lowest point in the area, and thus most of the surface water runoff drains into it, with serious pollution consequences. The municipality covers an area of 290 km^2 that includes the whole of Lake Nakuru National Park and the peri-urban agricultural settlements to the south-west of the town. Nakuru's population in the 1999 census was 231,000 individuals and with a growth rate of 3.8 per cent it is projected to reach 457,495 individuals in 2015 (GOK 2008).

The sample size and sampling procedure from household was perfromed as explained by Israel (2004) and Kathuri and Pals (1993). The sampling frame for households was taken from the total households as per the 1999 population census (Government of Kenya [GOK] 2008). A stratified random sampling procedure was employed using locations that are administrative units as different strata. These locations included Kaptembwa, Afraha, Lanet and Baharini. The size of each stratum was calculated proportionately based on the number of households per stratum over the total number of households in the municipality. A sample of 250 households was arrived at. The specific households were randomly picked with the aid of the software package SPSS via its “Select cases” procedure. The sample size of institutions offering services was 211 respondents. The sampling frame for these institutions was drawn from a preliminary study and the sample size for each institution calculated (Morris 2001).

Data were collected from the selected households and institutions, such as electronic repair shops, ICT training institutions and offices in Nakuru. Primary data were collected through the administration of a questionnaire that elicited information on the methods of e-waste disposal currently in use and the effects of poor e-waste disposal on human health and the environment. An observation schedule and photographs were used to verify the presence of e-waste in dump sites in the estates, the main municipal dump site (Gioto) and plastic recycling yards as well as in scrap metal yards.

Data were coded, entered and analysed using SPSS version 11.5. The summary and illustration of findings was done with descriptive statistics (frequencies and graphs). The Chi-square test was used to show the relationship between the type of institution, household and the method of e-waste disposal. The tests were performed at a 5 per cent level of significance ($\alpha = 0.05$).

Results and discussion

There are advantages associated with manual separation compared with the shredding and automated sorting of certain components of e-waste. For instance, the manual removal of circuit boards from telecommunication and information technology equipment prior to shredding has been found to prevent the loss of precious metals (UNEP and StEP 2009). The lack of technology and skills, unexplored business and financing opportunities coupled with an exponential growth in the use of electronic equipment in Kenya may lead to severe challenges in the proper management of e-waste (Waema and Mureithi 2008). Moreover, a regulatory framework for the management of e-waste does not exist in Kenya. Nevertheless the worldwide concern on environmental and human health problems associated with dumping e-waste and poor methods of recycling it has led Kenya, with the establishment of the National Environmental Management Authority (NEMA) and in partnership with UNEP and International Conferences Workshops and Exhibitions Africa to convene a conference on e-waste management to map the way forward for sustainable e-waste solutions (UNEP 2010). This conference was sponsored by Microsoft and Safaricom.

Figure 6.1 shows the methods used by residents to dispose of e-waste. Very little of the increasing e-waste being generated is being recycled. This raises concerns over the residents' ability to recycle e-waste and awareness of the related hazards. According to Babu et al. (2007), the successful recycling of e-waste depends on the cost of labour, the structure of the economy, the existing regulatory framework and the possibilities and limits of law enforcement. These factors must be considered in order to find solutions that can improve e-waste management in Nakuru and Kenya as a whole. The cost of labour is low in the municipality as many young people lack employment and are looking for a means of livelihood in the informal sector. If appropriate structures can be established these young people can be trained in the basic skills that will enable them carry out the manual separation of the components present in e-waste.

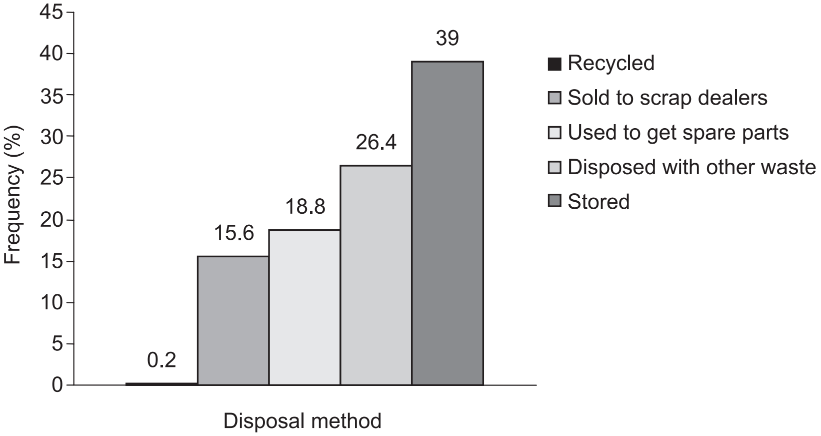

Figure 6.1 E-waste disposal methods commonly used

The volume of e-waste used to obtain spare parts or to be sold to scrap dealers (Figure 6.1) is an indication that there are social and economic advantages to the existence of e-waste such as the creation of new industries and employment opportunities. Electronic repair shops obtain broken and obsolete equipment from consumers who often do not come back for their electronic equipment once it has been found to be irreparable, due to the high cost of repair or if the spare parts needed are not readily available. They use this equipment for spare parts and stockpile the remaining parts in the shops, throwing away the smaller parts together with other solid waste. The scrap dealers working in electronic repair shops dismantle the equipment to extract the metallic components which they sell to scrap metal dealers. However, the techniques used to extract the spare parts are unsafe, and espose electronic equipment repairers and the environment to toxic substances. The e-waste that is collected mainly from residential areas in Nakuru municipality by these young men includes TV, computer monitors and audio-visual equipment.

The e-waste that is disposed of along with other solid waste is an indication of the lack of proper solid waste management in Nakuru. This issue can be addressed by revising the municipal by-laws on solid waste management to include the sorting of solid waste at the source. When e-waste is dumped with other solid waste in the municipal dumpsite, even in small amounts, it acts as a potent pollutant and contributes to toxic leachates and vapours, such as the vapourization of dimethylmercury. This can result in contamination of soils and water, especially in Lake Nakuru through surface runoff, exposing organisms and residents to toxic substances from e-waste and leading to ailments like cancer and other ill health (Ramachandra and Saura 2004). Furthermore, dumping e-waste leads to the loss of the valuable resources that are present in e-scrap, including precious metals. Figures 6.2 and 6.3 show e-waste and e-waste burning with other solid waste in the municipal main dump site, respectively.

Primary production of metals from mining the ore has been found to lead to significant environmental impacts in terms of energy use and CO_2 emissions. The high amount of e-waste in storage can provide an alternative source of the non-renewable resources, especially precious metals, through secondary production processes that use less energy and have low CO_2 emissions (UNEP and StEP 2009). The publicity given to the presence of precious metals in e-waste, especially in mobile phones, may result in informal entrepreneurs recycling e-waste without having the necessary technology to do so safely. This will have dire consequences on the environment and human health, as happened in Ghana and other developing countries. The Nakuru local authority needs to ensure that e-waste in households is safely collected and to design ways how it can

Figure 6.2 E-waste in the municipal dump (Source: photograph taken by researchers during the data collection)

Please see page 188 for a colour version of this figure.

Figure 6.3 E-waste burning together with other municipal waste (Source: photograph taken by researchers during the data collection)

Please see page 188 for a colour version of this figure.

be safely recycled that may avoid the dumping that leads to loss of these resources.

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Choice of e-waste disposal method

The relationship between the categories (households and institutions) and the method of disposal of e-waste was critically analysed using Pearson's chi-square statistic. The computed chi-square = 249.643, P-value = 0.00, implies that there was significant relationship at the 5 per cent level between the type of business and the method of e-waste disposal used. Repair shops mainly harness e-waste for spare parts, (56.8%), 18.2% store it, 22.7% sell it to scrap dealers and disposed of it with other waste and only 2.3% recycle it. ICT training institutions and offices keep most of their e-waste in storage and use it for spare parts. Households mainly keep their e-waste in storage (42.3%), dispose of it with other waste (35%) or sell it to scrap dealers (22.7%). The respondents may store their e-waste because they do not know how to dispose of it.

The analysis of the factors that influence their choice of e-waste disposal are: 'it is convenient to do so (32.9%)', 'cheap and convenient (26.5%)', and 'cheap (16.9 %)'. Of all respondents, 11.1% made their choice of method in order to save money on spare parts and 12.6% indicated that they did not know of any e-waste collectors. Most of the respondents use the e-waste disposal method they chose for convenience. This indicates that, with properly structured awareness educational programmes, residents may be receptive to suggestions on how best to dispose their e-waste.

Respondents' awareness of effects of e-waste disposal on health

Figure 6.4 shows the respondents' level of awareness of the effects of poor e-waste disposal of human health and the environment. Most of the residents lack awareness of the relationship between poor disposal of e-waste and human health but have some awareness on its effect on the environment. This lack of awareness is a major concern because it may influence the way people dispose of obsolete or broken electronic equipment. If their level of awareness w high, consumers would not dispose of their e-waste with other solid waste that is burnt at the municipal main dump site. This results in uncontrolled emissions of hazardous substances into air, soil and water. Some of these emissions into the air include extremely toxic dioxins and furans due to the presence of PVC and brominated flame retardants in electronic equipment (Babu et al. 2007). The relationship between the respondents' level of education and their level of awareness about the poor disposal of e-waste on human health and the environment was analysed using Pearson's chi-square statistics. The computed chi-square statistic = 7.176, *P*-value = 0.619 and 34.505, *P*-value = 0.000, respectively, shows that the respondents' level of education does not significantly affect their awareness of the effects of poor disposal of e-waste on human health but does significantly affect their awareness of the effects on the environment. The low level of awareness on the effects of e-waste disposal raises the question as to whether the curriculum offered in schools and institutions of higher learning adequately covers environmental issues. In view of this, an investigation of the suitability of environmental education offered at all educational levels to address emerging issues needs to be carried out.

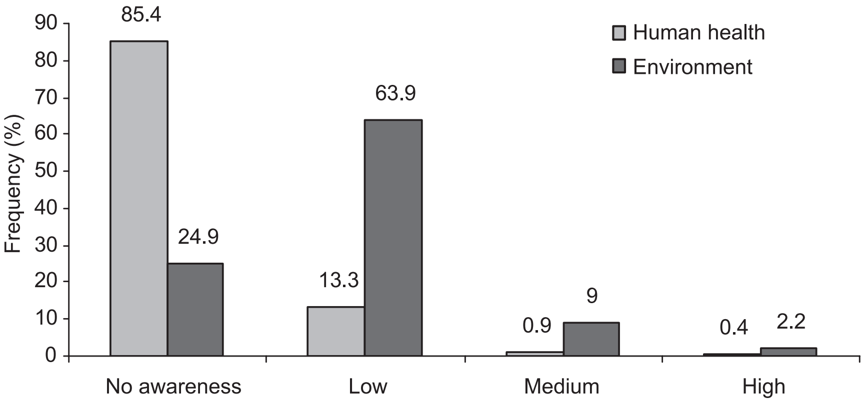

Figure 6.4 Level of awareness of effects of e-waste disposal

Conclusion

From this work it is quite clear that there are challenges facing e-waste management in Nakuru. The residents store their e-waste because they are not aware of better ways of disposing of it. This could also be motivated by their perception that these goods could still be valuable. Consumer education is of paramount importance to create the awareness needed for the sound management of e-waste not only in Nakuru but in Kenya as a whole. The government needs to set aside funds for more on e-waste ecycling, not only from computers but from other electrical and electronic goods. The residents' use of e-waste for spare parts shows that reusing e-waste can be very valuable and it is a practical example on how sustainability can be advanced. The local authority should identify actions different sectors can take in moving towards the sustainable management of e-waste and build partnerships with stakeholders to foster a more cooperative and holistic approach to creating sustainable e-waste management structures. These stakeholders include electronic equipment repairers, proprietors of ICT training institutions and institutions of higher learning. The government through NEMA should take centre stage in developing a nationally consistent approach for e-waste management that considers environmental and socioeconomic costs, benefits and impacts.

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Part IV

System design approaches for sustainable e-waste management

7

Covenant for an international system of sustainable resource management

Henning Wilts

Introduction

This chapter focuses on the development of international covenants – a special form of treaty based on private law – between the producers, collectors and recyclers of electronic products to improve the circulation of palladium in waste electrical and electronic equipment (WEEE). Used and waste mobile phones, in particular, are still being exported to developing countries as the current economic structure encourages this practice. These covenants could create, together with the European WEEE regime, the basis for an international system of sustainable resource management, which currently does not facilitate the recycling and protection of scarce metals like palladium. Based on an analysis of legal and economic structures, it addresses the question of how to increase resource productivity – the added value in relation to resource requirements – in the area of e-waste. From this perspective, a sustainable resource policy needs to take into account environmental protection (such as the reduction of the total material requirement or TMR) and social (such as employment and job security) as well as economic aspects (securing the supply of resources for the industry).

Product-related approaches to sustainable resource management

Every economic and social system and every entrepreneurial activity is based on the use of natural resources. The economic capital stock is built

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Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
United Nations University Press, 2013, ISBN 978-92-808-8035-9

on natural resources like raw materials and ecosystem-based services, such as our climate system. Given the limited resources and carrying capacities of ecosystems, economic development dependent on the increasing use of physical natural resources and ecosystems therefore cannot be sustainable in the long term (Bleischwitz 2009). Since environmental burdens are closely related to the extraction, use and dumping of resources and in light of the complexity of the relationship between the environmental and the "socio-industrial metabolism" (Bringezu and Bleischwitz 2009: 1), the resource productivity method aims to reduce the material throughput of socioeconomic systems as a whole. Various studies have shown that the consumption of resources explains much of the variance in the state of the ecosystems in industrial countries (Van Voet et al. 2005).

As a result, the EU sustainable development strategy has set the sustainable management of resources as a central objective: "improving resource efficiency, to reduce the overall use of non-renewable natural resources and the related environmental impacts of raw material use" (Eurostat 2009). But, as shown in Figure 7.1, a relative, but not an absolute, decoupling of resource consumption from GDP trends can be observed. Following the current trend, the German sustainability strategy to double commodity productivity until 2020 (relative to 1994) cannot be achieved. In addition, Germany is increasingly shifting the environmental

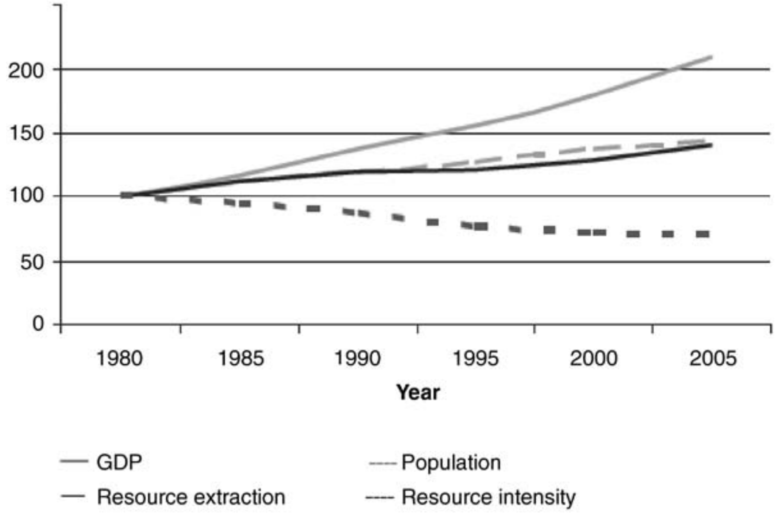

Figure 7.1 Evolution of resource consumption in Europe, 1980–2005
1980 = 100 (Source: Giljum et al. 2008)

impacts of its resource consumption patterns abroad by importing resource-intensive products. The share of imports, especially of metallic and semi-manufactured goods has more than doubled since 1994 (Federal Statistical Office, 2010).

The use of non-renewable metals is one of the key challenges of sustainable resource management (Giljum et al. 2008). Metals and ecological rucksacks associated with their primary production (the complete material input needed to produce the final raw material from the cradle to the point of sale), is one of the three main drivers of the total global requirement of raw materials (Acosta-Fernández 2007). From an economic point of view a more efficient use of metal is one of the crucial tasks of the future: companies depend on a secure raw material supply. Germany and the EU, as a resource-poor region, are highly dependent on imports of metals. The global demand for them is sharply rising, especially in countries like China and India. Simultaneously, for some strategic metals we can observe on the one hand increasing scarcities, and on the other hand a concentration of the remaining reserves in only a few states. The objective must therefore be a better circular conduction of metals, which is no technological problem. The challenge is mainly to manage the flows of material.

The environmental policies of the past 30 years have focused on preventing local or regional environmental impacts of pollution and the use of hazardous substances. Considerable success in this area has been achieved, as reflected, for example, in an improvement in water quality in rivers and lakes or the improved quality of air in large cities. Recent discussions about the human-caused climate change have shown that environmental problems have taken on a new quality. The costs of unsustainable resource use are often characterized by impacts that are shifted spatially and temporally. They are closely linked to consumption and production patterns and cause additional social and economic impacts. This complexity of different interactions makes them extremely difficult to manage or control.

Use of palladium in electronics

In 2008 about 41 t of palladium was required for electronic products, which corresponds to approximately 20 per cent of the amount mined worldwide (Saurat and Bringezu 2008). The main applications of this metal are the multi-layer capacitors (MLCC) used on printed circuit boards. Despite of declining amount of palladium needed per MLCC as a result of technological developments, the demand is increasing in this sector in recent years, on the one hand because of the increasing total demand for electrical and electronic equipment (EEE), but also because of the increasing complexity of products, with more MLCCs needed per product. In total 1.28 billion mobile phones were sold in 2008 worldwide, approximately 70 per cent of them to replace an existing device. The average useful life of mobile phones in developed countries actually is only 12–18 months. The average amount of palladium per mobile phone of 9 mg (Chancerel and Rotter 2009) corresponds to a total quantity of 11.5 t annually used for mobile phones. Experts estimate that large proportions are not collected by official recycling schemes but are exported for reuse, especially to developing countries (Johnson Matthey 2009). These exports support the construction of a communication infrastructure that in Africa is mainly based on used mobile phones, and ensure employment in the local informal repair and recycling sector. However, the lack of environmental standards for the recycling and the disposal of WEEE places heavy burdens on workers and, via the polluted groundwater, on the entire population in centres where electrical recycling takes place. Moreover, the recovery of precious metals is limited to extracting the gold, silver and copper content, so the palladium component is almost completely wasted as the technical requirements for recovering it do not exist in these countries. Investigations at the Wuppertal Institute on the resource intensity of primary and recycled (so called secondary) palladium (Saurat and Bringezu 2008) indicate which potentials to increase resource productivity are wasted by those missing circular flows (Table 7.1).

An analysis of the incentive structures influenced by the WEEE directive (2012/19/EU) shows that the existing institutional framework is not suitable for promoting the circulation of the platinum group metals (PGM) but instead provides additional incentives for their export and thus promotes their loss to high-quality recycling [de Bruijn and Norberg-Bohm 2005), as the reuse of EEE may not count in the recycling quota. For mass-based collection targets small electrical appliances do not matter, and this is not an issue in the revision of the WEEE directive.

Table 7.1 Comparison of environmental impacts associated with PGM primary and secondary production
(Source: Saurat and Bringezu, 2008)

Impact Indicator	Palladium	Platinum
Primary Production, TMR in t/t	99,891.12	683,564.91
Secondary Production, TMR	2394.01	873,882.00

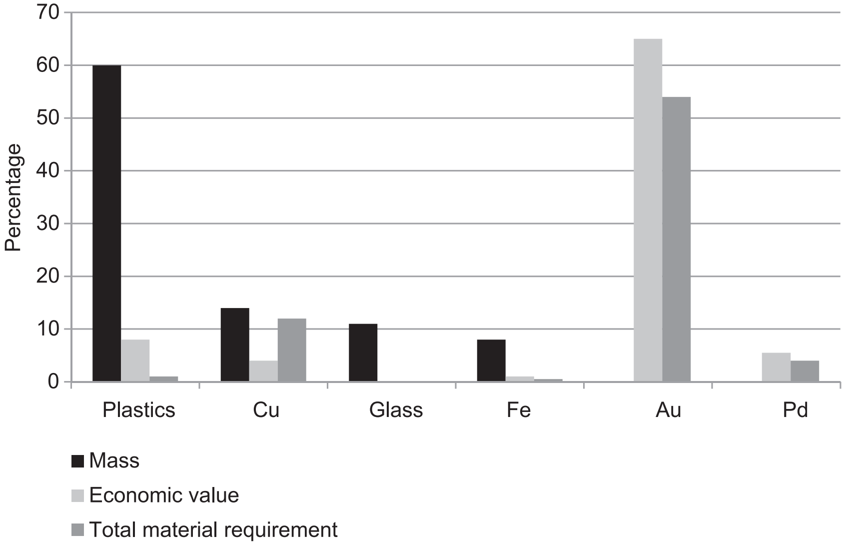

Figure 7.2 Proportion by mass, economic value and TMR of materials used in mobile phones. Au, gold; Cu, copper; Fe, iron; Pd, palladium
(Source: Chancerel and Rotter 2009)

High mass-based recycling targets lead to high costs for the entire system; including the cost of collection and recycling the total amount of investments has been estimated by the EU at €5.6 billion (European Commission 2008), but they also lead to the high legal second-hand goods export market and illegal waste shipments. Investigations have shown that the proper recovery of the PGM in Germany costs about €4 per device (and much more in Austria), while exports to Africa only cost about €1.50 (Hagelüken 2007). Figure 7.2 shows that the mass-based approach is ineffective for precious metals: palladium causes only about 0.005 per cent of the weight of a mobile phone, but causes 5 per cent of the TMR.

The high export rates also undermine the basic regulatory approach of the WEEE directive: the extension of the physical and financial responsibilities of producers to the end-of-life phase of their products. In fact, extended producer responsibility ER aims to set incentives for design of EEEs that can be easily recycled, if their end-of-life costs can no longer be externalized. These incentives are already significantly weakened by the collective collection of waste products, but if a relevant share of these products is exported and collected outside the WEEE collection system because it ends up in developing countries, this approach is completely foiled. An approach of global product stewardship not ending at the EU borders is, in our opinion, a prerequisite for true eco-innovations beyond slow and incremental improvements of the production of these goods.

New need for cooperation along the product life cycle

From a theoretical governance perspective the evaluation of the WEEE and the restriction of hazardous substances directive Directive (RoHS Directive 2002/95/EC) clarifies the limitations of direct state regulation of environmental policy. It is criticized because it shifts instead of solving problems and therefore does not promote but hinders innovation processes, causes significant difficulties in implementation and is generally linked with high transaction costs for all parties involved (Ökopol 2009).

Lack of knowledge and uncertainty in secondary raw material markets

The following section examines why the traditional instruments of environmental policies have largely failed and analyses the need for new resource policy instruments. Direct regulation by law is increasingly impractical because the administrative area and the topography of the real material flows no longer coincide. Moreover, a simple market solution is hard to imagine in light of the external costs of resource extraction and use. Nevertheless the extent of market failure is surprising, considering that the industry must be interested in a cheap and secure supply of raw materials. Why is it that not more than 3 per cent of the discarded mobile phones in Germany are collected and recycled (Nokia, 2008) although this could be a profitable field? According to Hagelüken (2010), only about 2 per cent of the global annual recycling potential of about 800 discarded mobile phones is actually recycled, equivalent to a loss of about 70 t PGM per year.

From our point of view this market failure is mainly caused by the transaction costs of gathering information about the place, time, quality and quantity of production inputs. The asymmetric distribution of information and knowledge deficits are therefore the focus of analysis, as the price discovery process is proving to be particularly difficult because of a lack of knowledge about the exact patterns of supply and demand. The transaction costs of acquiring information can be observed in all markets but they are particularly relevant in markets for secondary raw materials: Post-consumer waste is decentralized and thus demands much greater efforts on logistics systems than, for example, a mine. Moreover, it is much more difficult to assess the quality of waste than that of primary raw materials. The gathering of information about material flows thus becomes a relevant regulatory target.

Since in Germany only a small share of discarded products are currently properly recycled or disposed of within the country, the effects of information asymmetries are systemic in many respects:

- Under current international conditions high costs are generated in the form of environmental damage, social costs and market distortions.
- Consequent international costs cause distortions in the domestic market of material efficiency and resource conservation.
- Possible innovative exploitation paths and sustainable resource management are impeded.

Need for a governance approach

For the complex challenges of a transition towards sustainability in the circulation of WEEE scrap new and innovative approaches are needed to complement established command and control strategies. Such instruments must reinforce cooperation between public authorities, non-governmental organizations and businesses, thus strengthening the exchange of information between the actors involved. The necessary systemic innovations towards sustainability require access to complex information. A starting point for new policy instruments is the recognition that neither governments nor corporations alone are able to and have the necessary information or resources to effect the necessary transformation of society towards sustainability (Bleischwitz 2005; de Bruijn and Tukker 2002). They also bear too many risks for individual companies to shoulder on their own. As intermediate agents of sustainable change, networks influence the motives of the actors, make resources available and put pressure on their stakeholders to ensure compliance in different ways. One possible approach to such indirect forms of regulation is a covenant.

The covenant solution

Based on the deficits of circular flows of palladium and the limitations of regulating the exports of used electronic products to developing countries by law, the potential of an international covenant to increase material efficiency and resource conservation is analysed. These negotiated self-commitments between industry and public institutions constitute a kind of political treaty setting norms and standards for the behaviour of the actors involved, but they include from the start rules for their implementation (Engel 2002). Covenants are a hybrid between direct regulation by the state and self-regulation by the industry. In contrast to standard command and control strategies, covenants are negotiated but binding treaties based on private law between public institutions, industry and other stakeholders aiming at concrete long-term targets. The distinction between the covenant and other forms of voluntary agreement is that the implementation of covenants can be enforced their international civil procedures. Covenants are characterized by the following basic principles:

- Industry sectors commit themselves to long-term targets.
- These targets are based on negotiations with the relevant public authorities.
- In return, the public institutions guarantee a stable framework and a waiver of additional direct policy interventions over the duration of the treaty.
- Covenants are formulated as private, law-based treaties that include mechanisms for sanctions if the targets are missed, as well as procedures for adapting the treaty to changed external conditions.

A draft for such an international instrument has been developed in the project, material efficiency and resource conservation (Wilts et al. 2010). It represents an approach that could actually make a contribution to a reconfiguration to the recycling of both economically and eco-logically relevant material flows. The covenant could provide a framework to close circular material flows at an international level. The costs and benefits of increased WEEE recycling could be distributed efficiently along the complete value chain in order to overcome the existing prisoner dilemma. The recyclers could invest in necessary infrastructure if they obtain a reliable input for their facilities from new international redistribution systems for WEEE.

New collaborations between industrial sectors and public authorities would contribute to the reduction of the transaction costs of obtaining information. At the same time, such a project could increase control by national states – both WEEE importing and exporting countries – and the acceptance of the industry of such regulations. The extended responsibility of producers for the physical and financial effects of their products at the end-of-use phase would no longer be undermined by exports. This would set real incentives to reinforce a design for recycling, if a bigger share of WEEE really is recycled and not disposed of in developing countries.

Structure and necessary preconditions of a covenant

Such a covenant has to define the different responsibilities as well as the instruments for their operationalization, implementation and evaluation. The private partners of the treaty, industrial organizations or their associations, must commit themselves to ambitious targets of resource protection and the public authorities guarantee a stable and supportive framework for the duration of the treaty.

Characteristics of targets

The contract has to obligate industry partners to agree on goals that are well above an expected "business as usual" scenarios. There is a risk, particularly for long-term goals, that the targets that are defined can be achieved without further effort, just by the usual technical progress.

Sanctions against free riders

Experiences with environmental agreements have shown that a lack of public control and the prevention of free-rider behaviour of individual actors are the critical to the success of the instrument (Bressers 2003). In contrast to voluntary agreements, the covenant should be enforceable in court in principle. At the same time, effective mechanisms for dispute resolution and sanctions should be included in the contract in case contractors fail to meet their obligations.

The covenant should also agree on exact and binding reporting duties for the parties involved. This will improve the exchange of information between manufacturers, recyclers and public agencies and promote innovation processes by identifying potential cost savings and new ways to systematically increase the efficiency of the value chain. Similarly, the publication of the reports will also put pressure on individual actors if they fail to meet their obligations adequately. The covenant could also envisage the establishment of an expert group that evaluates the reports of the parties and decides whether the agreed targets and standards have been achieved.

Effects from a business perspective

The cost of negotiating and monitoring such an agreement as a substitute for direct regulation should not be underestimated. In extreme cases, the negotiation process may be even more time consuming than the process of direct regulation. Furthermore, a covenant prompts complex legal problems, such as how democratic states can commit themselves to contracts based on private law.

From our point of view neither too high expectations nor a fundamental scepticism towards covenants is appropriate. The instrument should not be considered as an isolated measure but as part of a comprehensive policy mix to increase resource productivity. Depending on the concrete configuration agreed upon, a covenant may have the advantage that all key stakeholders are involved in the negotiation process, which will both foster an efficient solution and increase the willingness of the parties to actually implement its results.

The field of recycling used products, therefore, seems to be potentially appropriate for a covenant. A single treaty could address high specific investments in recycling infrastructure, complex international bargaining processes with high uncertainties about framework developments, lucrative market potentials for material efficiency and resource conservation as well as including the different countries in which WEEE is exported.

One problem that might be encountered is the market structure for electronic equipment, which is dominated by modular networks with the manufacturers of the original equipment (Lauridsen and Jorgensen 2010) that, in comparison with the automotive sector, have only limited influence and knowledge about the resources used in their intermediate products. This aspect of agency should not be underestimated, but some companies like Apple have started to intensively control their supply chain (Apple 2010).

Covenants as niches for innovation

From a static point of view direct regulations or economic incentives clearly lead to more predictable results than covenants in order to improve the high-quality recycling of WEEE (Krarup 2001). But accepting the limitations of such instruments, there are innovatory effects to such second-best regulations. Among these are the dynamic effects of innovation, which increase in importance, especially in environmental policy. A covenant could constitute a knowledge-generating institution (Bleischwitz 2005) because it lowers the transaction costs of research for information through sector-wide cooperation and significantly stimulates learning processes in favour of system innovations. The covenant could form a technological niche in terms of transition management theory (Kemp 2010) where radical novelties may emerge, like new business models for the redistribution and recycling of mobile phones in developing countries. These novelties are start off as unstable socio-technical configurations with low performance. Hence, niches act as “incubation rooms” protecting novelties against mainstream market selection. Niche innovations are carried out and developed by small networks of dedicated actors, often outsiders or fringe actors that could be brought together in negotiating a covenant. From such a perspective it can be argued that transitions towards sustainability come about when niche innovations build up internal momentum through learning processes, price and performance improvements and support from powerful groups.

A key objective of the covenant is to encourage systemic innovations of flows of material. Companies should not only optimize their own internal processes but reduce material consumption along the entire value chain. Covenants can establish a basis for innovation process by nominating open orientation targets (e.g. doubling the productivity of resources or halving the total expenditure for materials by the year X). A common understanding of the problem to be solved between all parties is a fundamental requirement for system innovations. A sense of shared responsibility for the results could be fostered by joint dialogues and negotiations on possible actions.

Of course the question arises why companies should participate voluntarily in the negotiation of such a binding contract, which also constitutes a restriction of their entrepreneurial freedom of action. They might do so if the covenant combined strategic interests on different levels.

The recycling industry has to face the fact that e-waste is increasingly accumulating in emerging and developing countries. This is not only caused by exports of used and waste electronic equipment but also by an increasing amount of domestic WEEE. For example, Yu et al. (2010) estimate that by 2013 more domestic than foreign WEEE will be collected in China. Therefore, the recycling industry will be substantially interested in establishing redistribution and recycling infrastructure in these countries.

For the manufacturing industry the covenant offers the possibility of increasing the security of supply for critical metals by recycling secondary raw materials. The need to act arises not so much from the geological scarcity of these materials as from the concentration of primary deposits in specific countries, which are starting to take advantage of their monopoly (for example via export controls for rare earth elements in China). In this way the covenant could contribute to the reduction of costs of material (e.g. through information exchange, training and unified production standards) by improving access to secondary raw materials. These benefits have to be linked to concessions on environmental standards, which probably have to be lower than European standards in the beginning, but at the same time also to significant investments in recycling infrastructure.

In the end, however, it is clear that such a treaty cannot be achieved without the clearly expressed political will of the states involved. It requires a credible “shadow of legislation” (Töller, 2008: 282) to force the parties to seriously start negotiations. If this is not accepted, states must be willing to address the problem of exports and recycling of WEEE by direct regulation, even if this causes higher costs and lower incentives for innovation than a covenant would. And finally, the consumer also has to appreciate the efforts of front runners who are seriously taking responsibility for their products.

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8

Can WEEE regulate effectively for sustainable consumption and production?

Hazel Nash

Introduction

The significance of moving towards patterns of sustainable consumption and production (SCP) to achieve sustainable development has long been recognized. Notwithstanding the raft of multi-level governance measures, little progress thus far has been made to sever the link between the use of natural resources and economic growth (Jackson 2009, 8). Altering entrenched behaviour and attitudes poses a multifaceted challenge for law and policymakers at international, European and national levels. One of the prevalent mechanisms used by the European regulatory framework to incentivize changes of behaviour is the principle of extended producer responsibility (EPR). The EPR has become a means of promoting greater resource efficiency, eco-friendly design of products and smarter consumption in the regulation of waste management. Nevertheless, the extent to which EPR should be considered to be a complete decoupling tool is questionable.

The "Directive on Waste Electrical and Electronic Equipment" (hereafter, the WEEE Directive) is one of a number of EU directives underpinned by EPR. Considerable practicable and regulatory challenges have been experienced by EU member states and producers of electrical and electronic equipment (EEE) in implementing their obligations set out in the WEEE Directive (Watson and Crowhurst 2007, 164). Challenges associated with the implementation of the WEEE Directive were identified in a multi-phase empirical study undertaken by the Centre for Business

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Relationships, Accountability, Sustainability and Society and corresponding conclusions were also drawn by the European Commission's Joint Research Centre and the Institute for Technological Studies (2006) in their report entitled "Implementation of Waste Electric and Electronic Equipment Directive in EU 25". In response to the findings in the report, the European Commission published a proposal to recast the WEEE Directive (hereafter, the WEEE Recast Proposal). The WEEE Recast Proposal provides a vehicle through which weaknesses within the WEEE directive can be addressed in legislation. Following the adoption by the European Parliament on 3 February 2011 of a legislative resolution on the WEEE Recast Proposal under the ordinary legislative procedure, the Council of the EU reached political agreement on 14 March 2011. The European Parliament will conduct a second reading in plenary sitting scheduled for 30 November 2011.

Focusing on the regulatory framework for management of waste EEE (WEEE, also referred to interchangeably throughout this chapter as e-waste) as a case study, this chapter examines the practicable challenges faced in regulating for SCP in order to achieve the overarching objective of sustainable development. Drawing on a desk-based review of the legislation and the findings of a project funded by the Economics and Social Research Council, which examined the WEEE Directive and its transposition and implementation into UK law, this article explores the scope and limitations of the WEEE Directive in developing an effective regulatory structure for the achievement of SCP in the electrical and electronics sector. To this end, the chapter considers both the constraints of EPR, as enshrined in the WEEE Directive and the WEEE Recast Proposal. The article begins by considering SCP as an objective embedded within international and European policy. It then examines the ways in which the WEEE Directive and the WEEE Recast Proposal have incorporated SCP. Using findings from both a legal analysis and empirical research, the chapter explores the practicable effect of these measures in delivering effective SCP in the management of e-waste.

The role of sustainable consumption and production

Decoupling economic growth from natural resource use has long been recognized as fundamental to achieving sustainable development (United Nations General Assembly 1992). Principle 8 of the Rio Declaration on Environment and Development recognized the influence of consumption and production activities on finite resources and the environment. It emphasizes the importance of reducing and eliminating unsustainable patterns of production and consumption in achieving sustainable development.

This commitment towards the promotion of SCP was reaffirmed by states in the 2002 Johannesburg World Summit on Sustainable Development's Plan of Implementation. Part III states that "[f]undamental changes in the way societies produce and consume are indispensable for achieving global sustainable development. All countries should promote sustainable consumption and production patterns" (United Nations General Assembly 2002: Part III, para. 14). The commitment established by Part III of the Plan included development of a 10 Year Framework of programmes on sustainable consumption and production (10YFP). The aim of the 10YFP, set out in the Johannesburg Plan of Implementation, is to "support regional and national initiatives to accelerate the shift towards sustainable consumption and production to promote social and economic development within the carrying capacity of ecosystems by addressing and, where appropriate, delinking economic growth and environmental degradation through improving efficiency and sustainability in the use of resources and production processes and reducing resource degradation, pollution and waste"(United Nations General Assembly 2002: Part III, para. 15).

At the European level, the sustainable development strategy provides the strategic policy document through which SCP is identified as a paramount component of sustainable development. However, SCP is advanced more tangibly through dynamic policy frameworks such as the Communication on the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan (for further discussion, see Nash 2009, 496ff). The Review of the Community Strategy for Waste Management (European Council and the representatives of the governments of the member states, 1996) emphasized that law and policy proposals should be aimed at decoupling environmental impacts from economic growth through the principle of producer responsibility. The Sixth Environmental Action Programme (Decision 1600/2002/EC) seeks to ensure that measures and policies introduced by European institutions, particularly in priority areas like waste, reflect the overarching need to secure sustainable patterns of consumption and production. It endorses under Article 3(4) the need for the internalization of negative and positive environmental costs through the use of market-based and economic instruments.

The current unsustainable production and consumption patterns and resource inefficiency has been brought about not by an increase in human population alone, but as the result of unsustainable developments in the way we design, manufacture and consume objects in the modern world (Chapman 2005, 3). Realizing SCP relies on behavioural evolution and the creation of a virtuous circle incorporating life cycle thinking, stimulating demand for better products, supporting eco-innovation and encouraging consumers to make better choices (European Commission 2008, 3). It is clear that law and policy can play a significant role in reshaping current patterns of production and consumption by establishing structural changes and incentivizing design and purchase changes. Indeed, Johansson and Lindhqvist (2005, 967) consider that law and policy play a central part in supporting progress towards sustainable development at all levels by shaping the market-place and fostering innovation.

In order to build on policy and encourage a more rapid transition to SCP, the European Commission has introduced a number of directives that address issues of SCP. These measures impose responsibility on producers of certain waste streams, for example, the Packaging Waste Directive, the End-of-Life Vehicles Directive and the Batteries Directive as well as the WEEE Directive. All these directives apply the concept of EPR, which attributes to producers the financial responsibility of their products throughout the product's life cycle. Extending the responsibility of producers throughout the life cycle of their products, including the point at which products become waste, plays a key role in achieving the decoupling of economic growth from resource use. Internalizing the costs associated throughout the life cycle of a product, including the collection, treatment and recycling of the product, producers are incentivized to substitute materials and alter product designs to accommodate all phases of a products' life, including its disposal.

Achieving sustainable consumption and production in WEEE

The main objective of the WEEE Directive is to address the negative environmental effects associated with e-waste and the rising volumes in this waste stream by facilitating the separate collection and management of EEE by the adoption of EPR (Article 1; Recital 12). Gertsakis et al. (2002, 529) consider that, as a policy objective, EPR relates to the way in which SCP might be realized through increased levels of waste avoidance and resource recovery. Responsibility for achieving SCP is assigned to producers of EEE. The reason for producers forming the main addressees of the directive is because they have the greatest opportunities to contribute to meeting the goals of Article 1 (Roller and Fuehr 2008, 280). Recital 12 to the WEEE Directive states: "The establishment . . . of producer responsibility is one of the means of encouraging the design and production of electrical and electronic equipment which takes into full account and facilitates their repair, possible upgrading, reuse, disassembly and recycling".

The obligations contained in the WEEE Directive require producers to facilitate the dismantling and recovery for reuse and recycling of WEEE according to their market share by product type (Article 8(3)). These obligations include shifting the focus of designers and manufacturers to take account of maintenance, upgrade and after-sales service rather than just product design on the moment of transaction in the store (Chapman 2005, 182). Design for the environment is able to address many of the environmental issues throughout a product' s life cycle, reducing resource use along the entire life cycle (Gertsakis 2002, 521). Article 4 of the WEEE Directive encourages innovations in product design and manufacturing processes to facilitate greater dismantling, reuse and recovery. Investment in design for the environment has been limited by Article 8(2), which enables producers to meet their obligations in relation to the separate collection of WEEE either through a collective take-back system or through individual take-back schemes. As a result of the options member states have in determining the method of take-back of WEEE, Article 6 provides for the establishment of individual or collective systems for the treatment of WEEE. Individual systems are operated by individual producers who collect their own branded products at the point of discard, whereas collective systems operate on the basis that the responsibility of producers to take-back e-waste are discharged to third parties by financial means. While the WEEE Directive includes the more burdensome option for individual producer responsibility, this option is not mandated. This flexibility in securing producer compliance with their WEEE obligations has resulted to date in less focus on the upstream stages of product life cycles and design.

Indeed, findings from empirical research suggest that producers considered the first motivating stimuli for commencing eco-design activities to be compliance with the legislation (33%). However, just 17.7 per cent of Phase 1 participants planned to engage in redesign for disassembly, remanufacturing or recycling in light of their obligations under the WEEE Directive. This finding reflects the conclusions of Deathe et al. (2008, 328) who considered that "rarely do collective take-back programmes incentivize design for the environment. Therefore, using EPR to regulate for sustainable e-waste management has serious limitations for the point at which producers engage with their obligations. While the idea behind EPR is ultimately to promote greater resource efficiency and reduce the environmental impacts of products at their end-of-life, producers still are not provoked by this regulatory mechanism to reconsider their product designs.

Article 12 of the WEEE Recast Proposal seeks to extend producer responsibility further by enabling member states to encourage producers to cover the entire financial burden of collection facilities for WEEE from private households. Recital 19 provides: "member states should encourage producers to take full ownership of the WEEE collection in particular by financing the collection of WEEE throughout the whole waste chain, including from private households, in order to avoid leakage of separately collected WEEE to sub-optimal treatment and illegal exports". In this way, member states can encourage producers to cover the costs of collecting WEEE through their transposing national legislation. The additional costs to producers involved in the collection and recovery of WEEE may provide an incentive for improved eco-design that, in turn, would have a beneficial effect on the volume of WEEE being diverted from landfill. However, as is the case with much of the WEEE directive, this can be achieved only by raising consumer awareness of the environmental impacts of WEEE and the importance of separating these products from residual waste.

Moreover, Article 12 provides member states with the ability but not the obligation to extend producer responsibility, leaving it to each national government to determine the stringency of their national measures in the regulation and management of e-waste. In the UK, guidance on the transposition of EU directives steers policymakers towards full implementation that does not go beyond the minimum requirements necessary to ensure compliance.

The WEEE Directive is failing to achieve SCP due in part to its over-reliance on EPR as the mechanism for achieving SCP. As Participant ID17, Phase 2 observed: "producers, governments and consumers each have some responsibilities in this". While the WEEE obligations focus on the responsibilities of producers and retailers to ensure the separate collection and treatment of WEEE, they largely fail to address the overarching need to create a virtuous circle in which consumers make sustainable choices that, in turn stimulate greater life-cycle thinking and support eco-innovation in the design of products. This, coupled with the flexibility afforded by the European directives in relation to the means available to member states to govern the take-back of WEEE, has resulted in a weak regulatory framework for e-waste management.

The EPR system envisaged by the WEEE Directive is one in which e-waste is separated out from residual waste to be managed in accordance with best environmental options. Article 1 provides that the main objective of the WEEE Directive is the improvement of the "environmental performance of all operators involved in the life cycle of electrical and electronic equipment, e.g. producers, distributors and consumers". Nowhere in the WEEE Directive is the responsibility of consumers explicitly addressed. The separate collection and treatment of WEEE relies upon consumers discarding their unwanted product either through one of take-back schemes operated by a retailer or distributer or at a civic amenity site (Article 5). Either way, the effectiveness of e-waste management depends upon consumer awareness and understanding of the environmental and social harm occurring in the inappropriate disposal of WEEE. Participants involved in both the 2006 and 2008 surveys expressed concern for the level of reliance placed upon consumers implicitly in the directive for the achievement of the WEEE ambitions. One participant explained:

> . . . it's the biggest bugbear with this legislation, you know, it relies so much on people returning goods. And the only way that WEEE will increase recycling is changing people's attitudes and behaviour, which I know is difficult but this directive does nothing, I mean there's no requirement on people to take things back . . . particularly when most electrical goods are you know, are consumer related, you need to put some sort of pressure on them to make them segregate them and make them take things to the community sites. (Participant ID07, Phase 2)

This was reflected further by 80.8 per cent of Phase 1 participants who deemed the WEEE obligations to be ineffective in preventing household e-waste from entering residual waste streams. This was attributed to a lack of awareness and insufficient information imparted to consumers. Article 10 sets out the information that must be provided for users of EEE from private households. The responsibility to provide this information lies with the producer.

The WEEE Recast Proposal aims to increase the target for the separate collection of household and non-household e-waste from the current weight-based minimum target of 4 kg per head of population and replace it with a minimum collection rate of 65 per cent for producers or third parties acting on their behalf. According to the proposed Article 7, this percentage will be calculated on the basis of the average weight of relevant EEE placed on the market in the two preceding years. This target is to be achieved from 2016 onwards.

The response from industry has been generally critical of the proposed collection target. They argue that the 65 per cent target is impossible to meet due to the volumes of WEEE flow that fail to make it into the take-back system (Federal Association for Information Technology, Telecommunications and New Media 2009). Again, to achieve these increased targets changes to consumer behaviour are rerquired. Yet producers are unlikely to be supported in the extension of their responsibilities under the WEEE Recast Proposal without significant improvement is the dissemination of information, education and awareness-raising. This is something that stakeholders involved in the phases of the research, in the UK at least, considered to be significantly lacking in the management of

WEEE. Responsibility for leading on these issues was generally thought to lie with the state.

The provisions contained in the WEEE Recast Proposal seek to strengthen the existing requirements of the WEEE Directive through increasing volumes of separately collected e-waste, with producers taking on board the costs of these operations to encourage more sustainable patterns of production throughout the life cycle of the product. Consumer behaviour underpins any ability to meet increased targets, separate household collections of WEEE and changes to product choices at the point of sale. One tool available to help raise awareness of the environmental and human health implications associated with the inappropriate disposal of WEEE is provided by Article 8(3), which enables producers to display the costs involved in the collection, treatment and environmentally sound disposal of EEE to purchasers at the time of sale of new products. The Directive does not however, place a legal duty on producers to include a visible fee on the EEE. This reduces the effectiveness of these proposals:

> One thing that we are very keen on is . . . the "visible fee" . . . we feel that that way, at the time that the consumer purchases the product, because there's a monetary amount there, they recognize "Oh, it costs me money. There is an economic impact associated with the disposing of my old thing and buying the new one, and it's this monetary amount".

If producers included the visible fee this would help to inform purchasers, encourage consumers to ensure separate collection at the point of disposal, raise awareness of the environmental impact of EEE and influence product choices. The latter potential outcome would have the additional benefit of stimulating investment in product eco-design and manufacture since, according to Phase 3 research findings, the lack of consumer demand was considered by 48 per cent of participants to be a barrier to implementing eco-design. However, political reluctance to require producers to display the cost of separate collection and treatment of their product on top of the base unit price hinders changes in consumer awareness, purchasing behaviour and product demand. The continuing absence under Article 14(1) of the WEEE Recast Proposal of a legal duty on producers to include a visible fee on their EEE is likely to reduce the effectiveness of these proposals. After all, opting in to the visible fee may be detrimental to producers and to the operation of a level playing field for business due to the administration costs involved in setting up a visible fee system. In addition, producers will be reluctant to display these financial implications; legitimately fearful that it may damage their competiveness in what is currently a difficult economic climate. This indicates that the current and proposed WEEE obligations are not achieving front-loaded adjustments to the life cycle of products through design and resource efficiency to secure SCP.

Conclusion

Recital 2 of the WEEE Directive states that achieving sustainable development requires "significant changes in current patterns of development, production, consumption and behaviour" and that all stakeholders in the materials economy have a responsibility to consider their actions and choices. Improving the effectiveness of the WEEE Directive in delivering SCP requires the balanced allocation of responsibility for e-waste through apportioning it to business, consumers and the state. The current absence of clear divisions of responsibility for the WEEE obligations lies at the heart of many of the difficulties identified by this research.

Undoubtedly, EPR widens the scope of responsibilities for producers over the life cycle of their products, but it does not address the existing social norms of behaviour prevalent in western societies. Nor does EPR address the intrinsic dependency of the WEEE requirements on other stakeholders, particularly consumers and the state, which underpin a practical transition towards SCP. Consequently, the persistent focus on EPR as the main regulatory mechanism is unlikely to achieve effectively SCP in EEE. The practical challenge of achieving SCP through the adoption of EPR measures in regulation is inflated by addressing responsibility in isolation, most of which is allocated to producers. Watson and Crowhurst (2007, 171–172) remark that the extent to which the WEEE Directive can achieve high levels of separate collection and encourage shifts towards sustainable consumption without putting legal obligations in place for consumers is a point of interest worthy of research.

Findings from the desk-based review and the three empirical research phases demonstrate that while EPR increases burdens on producers, through enhancing the responsibility they have towards the products they manufacture, its impact is significantly diluted by operational measures that enable producers to collectively meet their obligations. The WEEE Recast Proposal falls short of addressing this issue through the withdrawal of the enabling provision relating to collective schemes and the requirement of individual producer responsibility systems. Furthermore, the difficult area of consumer responsibility in the sustainable management of e-waste continues to be evaded in the WEEE Recast Proposal, although consumption and consumer behaviour do need to be tackled if SCP is to be secured.

Achieving SCP in e-waste requires an explicit allocation of responsibilities between the various agents in the life cycle of products. This is no mean feat for legislators at European or national level since it requires a fundamental step change in (i) the nature and character of political institutions that are repositioned to build long-term alterations in society to achieve sustainability; (ii) the reality of social and economic structures that better reflect the costs of industrialization and consumption; and (iii) the redesign of regulatory and policy mechanisms that develop synergies supporting a shared responsibility to protect and enhance the common good. This may include the move away from the use of directives in order to both prevent a race to the bottom and their ineffectiveness due to disputes over responsibility. In this way, administrations have the primary responsibility in realizing SCP through the acknowledgement, at legislative and policy levels, of the importance of apportioning responsibility.

While the WEEE Recast Proposal should be welcomed as a step towards a more effective e-waste management system, it is questionable whether it goes far enough to achieve greater patterns of SCP. Much is left to member states to determine and thus the strength of the WEEE Recast Proposal relies on commitment and strong directed and supportive governance at member state level. The regulatory emphasis remains on EPR, which is unlikely either to provide dramatic revisions in product design or aid changes to consumer behaviour and choice. While the European Parliament have delivered revisions following the first reading, alterations should still be expected as the WEEE Recast Proposal moves forwards through the ordinary legislative procedure.

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9

Exploring a third-party e-waste recycling system under the extended producer responsibility framework in China

Hua Zhong and Shu Schiller

Introduction

The rapid advance of information technologies has produced a large amount of waste of electronic and electrical equipment (WEEE). WEEE or e- waste, refers to old, end-of-life (EoL) or discarded electronic appliances. The world produces 20 to 50 million metric tons of e-waste annually (Electronics Take-back Coalition 2009), of which China alone contributes 2 million tons. Each year at least 6 million washing machines, 7 million TV sets, 10 million PCs and 70 million mobile phones are discarded and the number increases at the rate of more than 10 per cent each year (Hung 2007), according to the report from the resource and environment comprehensive utilization department of the State Development and Reform Commission (SDRC 2006). Discarded electronic products contain a stew of toxic metals and chemicals such as lead, mercury, cadmium, chromium and polychlorinated biphenyls (Scott 2007) and cause great harm to the environment. Recycling and reusing e-waste are thus becoming an increasingly important global issue.

Extended producer responsibility (EPR) is defined as "a policy principle to promote total life-cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life-cycle of the product, and especially to the take-back, recycling and final disposal of the product" (Lindhqvist 1992). The ultimate goal of controlling e-waste is minimizing

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the impact on the environment of EoL products. E-waste recycling involves product and systems design that take EoL products into account. In order to fully integrate product retirement concerns into design considerations, it is necessary to gather feedback and internalize costs and data. Although EPR determines that producers have leading responsibility in this, other parties, including consumers, retailers, recyclers and governments need to contribute to this process.

Extended producer responsibility practices

Definition and legislation in different countries

The extended producer responsibility (EPR) concept was first formally used in Sweden by Thomas Lindhqvist in 1992 in a report to the Swedish Ministry of the Environment. The Swedish reports further specified how manufacturers should take responsibility for their products, including their liability, and their responsibilities in terms of the economic, physical and information aspects of doing so. In 2000 the European Parliament passed a directive requiring its member countries to institute EPR programmes for EoL vehicles (Forslind 2005) and an additional directive for waste electronics and electrical equipment (WEEE) was approved in early 2003. This is not only a European phenomenon; as, for example, Japan has also enacted an EPR law covering four large electrical home appliances (TV sets, refrigerators, air conditioners and washing machines) (Spicer and Johnson 2004). The USA established a similar system with variations focusing more on product responsibility, instead of products themselves. Table 9.1 shows the definitions and explanations of EPR in respective legislations.

In addition, scholars have explored relevant practices in different regions (such as Sweden, Germany, the USA, Japan and Taiwan) and across different products (printers, PCs, motor cars and batteries) (Forslind 2005; Hanisch 2000; Lee 2008; Mayers 2005). They reached a consensus recognizing that EPR policies can actually stimulate product innovation and environmentally friendly design in reducing the use of materials, resources and energy by eliminating the use of toxins, extending the useful life cycle, increasing opportunities for the recovery and reuse of products at their Eo and creating new forms of product delivery, such as a leasing product service system (McKerlie 2006; Nicol and Thompson 2007; Tojo 2001).

Table 9.1 Definition and EPR legislation in Europe

	Europe	Japan	USA
Legislation	WEEE Restriction of Hazardous Substances Package and EOL Vehicles	Home Appliance Recycling Law	Extended product responsibility The state of California imposed an electronic waste recycling fee on new purchases of electronic products with viewable screens.
Responsibilities			
Producers	Collection, recycling, disposal and charging the fee	Complete recycling rate index	
Consumers	Pay the recycling fee and insure the integrity of e-waste	Should inform the retailer when home appliances retire	
Government	Pay a part of fee of collection, disposable or make policy of fiscal subsidies of EPR organization	Enforce legislation	In EPR system, producer, supplier and customer take on responsibility for the environmentally appropriate disposal of e-waste

Extended producer responsibility modes of implementation and capital operation

Depending on how thoroughly it is implemented and how much the government is involved, there are three models of EPR implementation. The first is the voluntary model, that is, producers take measures to decrease the impact of their products on pollution. For example, enterprises devise a take-back plan and recycle their products at their EoL. The second is the enforcement model, as obligated by the government, in the government forces manufactures to recycle their products. The third is the economic model, realized by incentives such as an ecology tax, pre-fee for recycling, and deposit return (Wanggan 2006).

In terms of capital operations, in Europe, Korea and Taiwan the cost comes from the producer, while in Japan it comes from the consumer. The USA is an exception. With no legislation on the EPR principle, it refuses to impose a burden on the original manufacturer [Wu et al. 2008)] arguing that this model is not appropriate to keeping the lowest social cost.

The take-back model

There are three EPR take-back models: original equipment manufacturer (OEM), pool and third-party take-back. The OEM take-back model is an EPR system in which the OEM themselves take physical and economic responsibility for the products they have manufactured. In the pooled take-back model the physical and economic responsibilities for products are assumed by consortia of manufacturers, usually grouped by product category. The third-party take-back model is an alternative approach where private companies assume EoL responsibilities for products on behalf of the OEM. In such cases the OEM pays a fee to a product responsibility provider, who then undertakes to ensure that the manufacturer's products are retired in a way that is environmentally responsible and compliant with EPR legislation. The basis and standards underlying these models and their effects have been compared. The OEM take-back model has an advantage in feedback, since the manufacturers are simply directly responsible for their own products at EoL. Therefore, this is more feasible for big companies than small ones, but it raises a barrier of scale for small companies and cannot resolve the problem of orphaned products, while the pooled take-back system can address the issues on orphaned products. However, it is impossible for pooled systems to gather feedback from economic indicators and achieve the goal of sharing information and closed-loop recycling. In contrast, the third-party take-back model has advantages for both manufacturers and the general public and appears to be a promising approach in optimizing product design, specialization, immediate economic feedback and demanufacturing market development (Spicer and Johnson 2004; Zhong and Schiller 2009).

China's implementation of extended producer responsibility

China takes the long view in the exploration and practice of e-waste recycling. Government agencies deployed four national pilot projects for WEEE recycling and management between 2003 and 2005, in Beijing, Tianjin, Qingdao and Hangzhou. The typical process of Chinese legislation is to first formulate lower level ordinances and regulations, then to gather detailed information in pilot studies, and finally, to draft a national law on a particular issue (Yang 2007). Legislation relating to e-waste recycling includes “The People’s Republic of China Solid Waste Pollution Prevention and Control Law”, “The People’s Republic of China Cleaner Production Promotion Law”, “Discarded Household Appliances and Electronic Products Pollution Control Technology Policy”, “Electronic Information Products Pollution Control Regulations”, the recent “Subsidy Program for the Replacement of Household Appliances” and the forthcoming “Waste Electrical and Electronic Product Recycling Regulations”.

Although we may glimpse EPR concepts in these regulations, as at the time of writing there has still been no clear definition of EPR practice in China. As a result, as far as collection and recycling networks are concerned, very slow progress has been made, and this has become a bottleneck to recycling. The key obstacle is that the costs are higher than they are when EEE is collected informally. In other words, it lacks a coordinating mechanism to stimulate and engage all parties involved in the recycling process.

In current conditions it is not realistic for China to aim at the voluntary implementation of EPR. In addition to a legal obligation, the country needs the help of third-party take-back economic methods to push for the adoption of EPR, especially if this is an efficient profit model involving integrative, systematic optimum mechanism design to realize efficiency in recycling e-waste.

Building an extended producer responsibility third-party e-waste recycling system

Overall framework

In response to the existing problem and in accordance with the principles of standard recycling, scientific classification, specialized disposal and the harmless reuse of products, this chapter develops a model of a scientific e-waste recycling system (EWRS), addressing both the collection and disposal of e-waste. This system, as a third-party recycling organization, aims to engage the interests of all stakeholder: producers, consumers, government, retailers and disposal sites; and achieve the dynamic control and management of all the relevant processes by applying an e-commerce platform (see Figure 9.1.).

Analysis of the stakeholders in the recycling platform

All recycling systems comprise a reverse supply chain. A system mechanism design should coordinate all stakeholders, whose responsibilities and obligations in the platform are discussed later in this chapter.

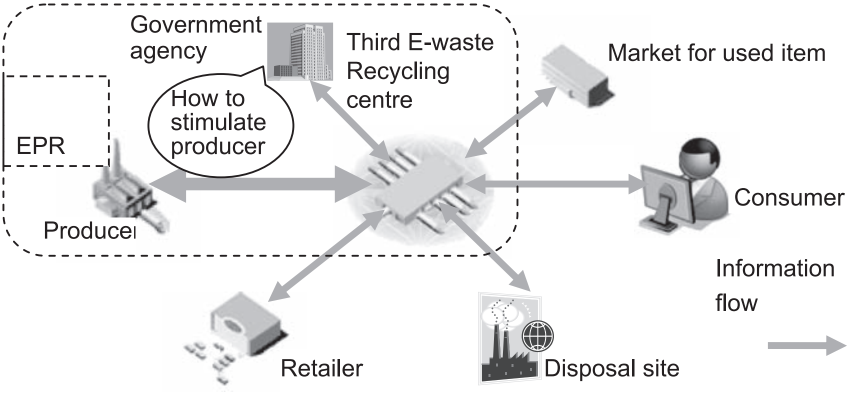

Figure 9.1 EPR Third-party e-commerce recycling system framework

The consumer, a supplier of e-waste, plays an important role in the reverse supply chain. Therefore, motivating the consumer is the key to the recycling platform operations. The system should take into account the consumer's bargaining power in order to avoid the deal failure. In particular, the recycling price should be based on analysis of the demand by interviewing consumers.

The recycling centre, as the provider of product and the reverse supply chain plan, has a close relationship with the original manufacturers through a contract with the principle agent. It receives e-waste collection and recycling fees from these producers together with government subsidies, and gathers revenues from the second-hand market by selling refurbished products. The core tasks of the recycling centre are to take a reasonable inventory, realize management scalability and maintain sustainable business.

The producer, as the EPR performer, is the real heart of the recycling system. On the one hand, from the viewpoint of a restraint mechanism-based contract of commission, the producer must pay a disposal fee in accordance with the complexity of disassembly of a particular product. As a result, producers will naturally be motivated to improve their product design. At the same time, from the standpoint of motivation, the government should offer subsidies and a refund mechanism or encourage compliance via a carbon tax, in order to encourage producers to fulfil their social responsibility.

The government, as the agent of enforcement, must focus on making efficient policies that provide incentives to producers, consumers and recyclers simultaneously in all the recycling systems in the large-scale control process. For instance, central government can focus on making policies for allocating funds for subsidies and creating standards and objectives, together with supervising the EPR system.

Recycling system process design

Using an online system, consumers will submit the e-waste information, including the product category, brand, model, purchase date and its current condition via the internet or over the phone. The system will then automatically generate a list of the items to be recycled, which will be picked up by professionals from a third-party recycler. The recycling price will be decided by the special assessing system. After the transaction, the third-party recycler will pay the consumer over the internet or in cash. The e-waste will then be transferred to an e-waste recycling centre, a third firm dedicated to recovering reusable materials from EoL products and selling them in second-hand markets. Once it has been delivered to the recycling centre, the e-waste will first be inspected to determine whether it can be repaired or should be disassembled. Repaired products could be sold in second-hand markets, while disassembled EoL products will be separated into reusable, recyclable and disposable materials, sending each to its appropriate inventory. The reusable and recycling components will be tested for their usability potential before they are sent to a producer or retailer, and the disposable components will be sent to the disposal site (see Figure 9.2). At the same time, the government will provide

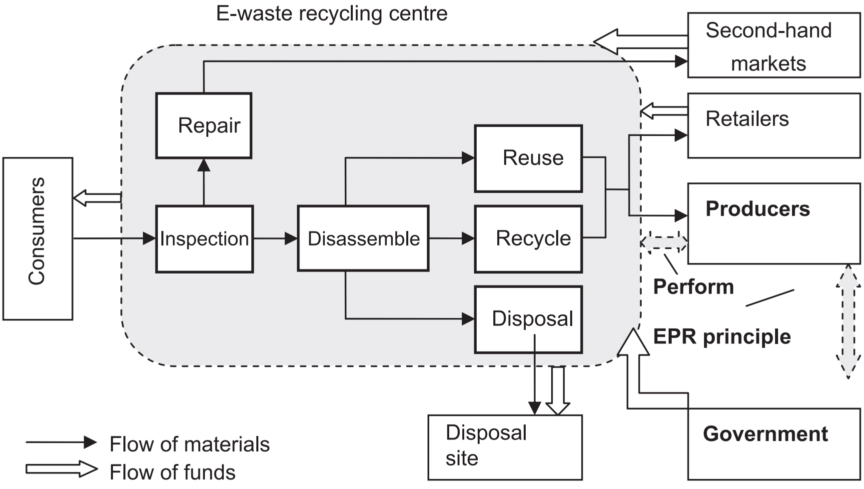

Figure 9.2 E-waste recycling process

the subsidy to the recycling centre or to the producers to realize the EPR principle.

The way in which the EWRS fulfils the EPR responsibility is the key to this system. The following two points need to be addressed: how to define the contract between the producer and the recycling agency and how the government should help to provide incentives to the producer. In light of economic realities, the government should assess the producer's contributions when establishing subsidies for recycling and disposal. Forthcoming legislation on "Waste Electrical and Electronic Product Recycling Regulations" clearly proposes that the government establish the foundation for the subsidy of recycling WEEE, and that both the collection and subsidy guidelines incorporate input from manufacturers, recycling firms and relevant experts. Therefore, the EPR principle is already involved in the proposed regulation and needs to be reflected through a reasonable contract and pricing mechanism.

E-waste recycling information system design

The e-waste recycling information system is composed of five modules to support the functionalities and business operations of the third-party recycler (Table 9.2). The client management module provides for real-time, online inquiries for recycling orders and processing information. The recycling processing module manages the recycling centre and documents information about the repair, disassembling, refurbishment, recycling and disposal of electronics. The inventory is maintained in the inventory management module. The information system also includes accounting functionalities to process, analyse, and report and manage costs. The logistics module collects, processes and presents information to support the reverse supply chain through which producers become recipients of recycled items.

Table 9.2 E-waste recycling management information system

Recycling	Inventory management	Accounting	Logistics
Client order processing	Inventory monitoring	Cost analysis	Reverse logistics
Recycling centre management	Stocking and processing	Analysis and reports	Information collection
Disposed products management			

Conclusion

In summary, this proposed e-commerce third-party e-waste recycling system has three benefits for efficient recycling and pollution reduction within the EPR framework:

- It will strengthen the theoretical system of EPR and explore a performance path for developing economies, offering increased economic incentives to stimulate all parties to become involved in the recycling process.
- It will increase recycling efficiency with the help of advanced information technology from the e-commerce information system.
- Using the third-party recycling platform as link, it will balance the interests of all parties and achieve a win–win situation all around. Consumer will be able to have their e-waste conveniently recycled and then receive economic compensation in return. Third-party recyclers can use the e-commerce platform to collect recycling items on a large scale and generate profits by disassembling and refurbishing them. Manufacturers can fulfil their social responsibilities and improve their corporate image by taking partial financial responsibility for the recycling process according to contracts between them and the third-party recyclers. The government will regulate the behaviour of all parties through policies and regulations and thus promote societal sustainable development, as well as peaceful coexistence between human beings and the environment.

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Part V

Technological challenges and innovations in managing e-waste

10

Bioleaching of polymetallic industrial waste using chemolithotrophic bacteria

Gregory Lewis, Stoyan Gaydardzhiev, Stoyan Groudev, David Bastin and Pierre-François Bareel

Introduction

Metal-bearing waste from various origins (such as end-of-life vehicles, waste electric and electronic equipment, metallurgical slags and white goods) are often recycled using post-shredder techniques encompassing gravimetric, magnetic or eddy current separation stages. During this treatment, large amounts of organic materials (including plastics, foam, textiles and other polymer-type materials) are generated, especially when end-of-life vehicles predominate in the input stream. Nowadays this material is most often dumped in landfills. However the stringent regulations for discarding goods and the associated high costs of dumping them render this option less preferable. Moreover, these waste streams could be regarded as secondary resources of metals (ferrous, non-ferrous and precious), ceramics and glass, provided suitable extractive technology is available.

Industrial waste containing non-ferrous metals are in general recycled via pyrometallurgical treatment with an almost complete recovery of metals (Cui and Zhang, 2008). At the same time, recent advances in the hydrometallurgical extraction of metals have increased interest in the integration of hydrometallurgical processes in the global treatment flow sheets (Cui and Zhang, 2008). The principal advantages of hydrometallurgy when applied to recovery of base metals such copper, zinc, aluminium and lead are summarized as follows:

Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
United Nations University Press, 2013, ISBN 978-92-808-8035-9

- low temperature process with low emission level of greenhouse gases
- better selectivity in downstream metal recovery
- small-scale installations offering higher flexibility

When leaching is performed in sulphate systems, lead and precious metals are not brought in the pregnant solutions but after solid or liquid separation they remain in a solid phase from which they can be recovered.

The use of microorganisms to make metals from waste soluable could offer a low-cost alternative to the classical hydrometallurgical processes. Bio-assisted solubilization can be utilized to oxidize zero-valent copper through leaching by iron (III) ions and sulphuric acid, where iron (II) oxidation or regeneration is carried out by the microorganisms. Several studies have been performed recently, mainly for recovering metal from printed circuit boards and various technological aspects were discussed by Brandl et al. (2001) and Ilyas et al. (2007). Bioleaching was also investigated by Mishra et al. (2008) for recovering lithium from spent secondary batteries.

This chapter discusses the results of bio-assisted leaching of a metal-bearing fraction derived from the catalytic cracking of a particular stream of shredder residues. According to our knowledge, the bioleaching of such of metal-rich waste has not been attempted so far. Due to the specific character of this solid waste and with the aim of proving the feasibility of this approach, it was necessary to follow the evolution in strain diversity and in the bacterial population expected due to effects accompanying metal–bacteria interactions. Therefore, a series of experiments was performed upon the effect of adding pH, nutrient medium, temperature and level of ferrous and ferric ion on the catalytic activity of the chemolithotrophic acidophilic bacteria used. The results obtained serve to elucidate the role of the bacterial consortium composition and to propose a qualitative model of the interaction between metallic copper and bacteria.

Materials and methods

Metal concentrate

During the low temperature catalytic cracking of shredder light-fraction residues in a pilot scale reactor, a liquid fraction (petrol) and the metal-bearing carbon residue were obtained. The metals from the carbon residue were subjected to gravimetric separation to yield the concentrate subject of the present investigation. The chemical composition of this concentrate (Table 10.1) suggests that the principal metals are iron and copper, with a minor presence of zinc and lead. An appreciable amount of glass was also present. Before leaching, the material was demagnetized

Table 10.1 Composition (w%) of the four products derived from the catalytic cracking reactor

	LOI	Fe	Cu	Zn	Pb	SiO_2	Al_2O_3
Carbon-bearing	41.2	6.7	0.7	1.3	0.4	12.5	10.21
1st mixed	19.6	6.8	0.8	1.4	0.4	–	–
2nd mixed	9.8	7.2	0.7	1.1	0.4	43.5	10.0
Metal-bearing	1.7	8.3	7.5	1.0	1.8	30.1	9.6
Total	28.1	7.2	2.1	1.2	0.7	–	–

Al_2O_3, aluminium oxide; Cu, copper; Fe, iron; LOI, lost on ignition; Pb, lead; SiO_2, silicon dioxide; Zn, zinc.

Table 10.2 Results of the magnetic separation of the input metal-bearing fraction with a neodymium magnet (wt %)

	Composition				Distribution			
	Fe	Cu	Zn	Pb	Fe	Cu	Zn	Pb
Magnetic	50.7	1.2	1.1	0.3	62.4	2.6	9.1	1.3
Non-magnetic	4.5	6.7	1.7	3.1	37.6	97.4	90.9	98.7
Total	10.4	6.0	1.6	2.7	100.0	100.0	100.0	100.0

Cu, copper; Fe, iron; Pb, lead; Zn, zinc.

Table 10.3 Results of the magnetic separation of the input metal-bearing fraction with a ferrite magnet (wt %)

	Composition				Distribution			
	Fe	Cu	Zn	Pb	Fe	Cu	Zn	Pb
Magnetic	41.1	2.1	2.8	0.4	93.1	8.8	47.9	4.9
Non-magnetic	1.0	7.5	1.1	2.8	6.9	91.2	52.1	95.1
Total	12.1	6.0	1.5	2.1	100.0	100.0	100.0	100.0

Cu, copper; Fe, iron; Pb, lead; Zn, zinc.

in order to reduce the concentration of iron-bearing components. This dry demagnetization was performed using neodymium or ferrite permanent magnets. Tables 10.2 and 10.3 summarize the results of metal partitioning in the magnetic and non-magnetic fractions.

Microorganisms and nutrient media

The bacterial culture used in this study contained a mixture of three different species; *Thiobacillus ferrooxidans*, *T. thiooxidans* and *Leptospirillum ferrooxidans*. To prevent the inhibition of bacterial activity due to elevated concentrations of metal in the leach solutions, a consortium was adapted of up to 20g/L copper using subsequent inoculation steps (Choi et al. 2004). Initially the cultures were routinely maintained by serial transfers in a 9K medium, as suggested by various authors (Das et al. 1998; Rossi 1990; Silverman and Lundgren 1959). Later, an active late-log-phase culture was transferred for inoculation inside a 2 L fermenter which was further used for the continuous production of the leach solution. The enumeration of cells was carried out using a serial end-point dilution technique, commonly known as the method of the most probable number (Karavaiko et al. 1988). For this task, three different media, Lundgren–Silverman 9K (Silverman and Lundgren, 1959), Mackintosh and Baering were chosen for the selective isolation of *T. ferrooxidans*, *L. ferrooxidans* and *T. thiooxidans* strains. While the composition of the 9K medium is well known, the Mackintosh medium is composed of ammonium sulphate 0.07 g/L; potassium di-hydrogen phosphate 0.01 g/L; hydrated magnesium chloride 0.03 g/L; dihydrated calcium chloride 0.07 g/L; heptahydrated ferrous sulphate 15 g/L; manganese chloride 0.03 g/L; zinc chloride 0.03 g/L; cobalt chloride 0.03 g/L; boric acid 0.05 g/L; sodium molybdate 0.01 g/L; copper chloride 0.03 g/L and the Baering medium of: sodium thiosulphate g/L; potassium hydrogen phosphate 0.1 g/L; sodium bicarbonate 0.2 g/L and ammonium chloride 0.1 g/L. The cell count in the fresh leach solution revealed that *T. ferrooxidans* is the most abundant culture with 2.5 10^6 cells/mL, followed by *L. ferrooxidans* with 4.5 104 cells/mL. As the material is free from sulphur and other reduced sulphur components, *T. thiooxidans* seems to be progressively depleted during the replication and inoculation stages and thus is present at very low level (2.5 102 cells/mL). The efficiency of the bacterial consortium in terms of the iron oxidation rate was evaluated by the consecutive inoculation of bacterial solution (10% v/v) in the 9K medium (90% v/v), with ferrous iron oxidation kinetics being assessed by an iron (II) titration over time.

Bioleaching

A two-stage bioleaching process was envisaged, encompassing the separate production of the leach solution and leaching. The leach solution was produced in a batch in a bacterial oxidation fermenter filled with ceramic rings for biofilm formation and inoculated with the consortium culture adapted to the material (at solutions with a copper concentration of up to 20 g/L). The volume of the leach solution was periodically drained out and the fermenter refilled with a fresh 9K medium. At the beginning of the leaching experiment, a 10 per cent (w/v) inoculum produced by the fermenter was mixed with a 90 per cent (v/v) of 9K medium and placed in a thermostatized 1 L double-walled leaching reactor. The solid material was subsequently added to form a suspension with a 10 per cent density of solid material (w/v), a value suggested and discussed in the literature (Brandl et al. 2001; Ilyas et al. 2007). The reactor was equipped with stainless steel stirrer and agitator (RW20 Janke and Kunkel) and run at 800 rpm. A pH electrode was placed directly inside the agitation vessel and a micro pump (ProMinent) dosing diluted sulphuric acid was connected to a control and acquisition system (Consort R305) operating in pH static mode. The pH value was set to 1.9 in view of the optimal growth of bacteria and for preventing an excessive built up of ferrous hydroxides that could induce copper loss. Parallel to pH, the Eh value (versus the standard hydrogen electrode) was measured and noted online by a PC as well. The bacterial leaching progress was followed by the regular sampling of the pulp. Aliquots from the pregnant leach solution were also regularly withdrawn for microbiological characterization. Each time a sample was taken, an equivalent amount of fresh 9K nutrient medium was added.

Sterile controls were performed in parallel to the bacterial leaching in order to evaluate the existence of oxidation and leaching on a purely chemical basis. Two tests were performed in this direction. The first was done by mixing 2.5 per cent (v/v) thymol directly with the fresh bacterial solution coming from the fermenter prior to the addition of the solid material. The second test used an oxidizing solution containing 9 g/L iron (III) from the dissolved ferric iron sulphate hydrate. The operating conditions for the leach tests performed are presented in Table 10.4.

Method of analysis

Copper, lead, zinc and iron in the leach solutions were analysed by atomic adsorption spectrometry or by inductively coupled plasma (using an

Table 10.4 Leaching conditions for the five tests performed

Test	Bacterial inoculum (%)	Fresh nutrient (%)	Initial iron (gL)	Other	pH	DP (%)	Temperature (°C)	Leaching time (hours)
1	0	0	0	Only H_2SO_4	1.9	15	35	7
2	10	90	9.0	–	1.9	10	35	144
3	100	0	8.2	–	1.9	10	35	142
4	100	0	7.6	+thymol	1.9	10	35	143
5	Pure chemical Fe (III)		7.4	–	1.9	10	35	144

DP, pulp density; Fe(III), ferric oxide. Test 2: 10% bacterial solution from the fermenter and 90% nutrient medium (9K), bioleach. Test 3: 100% bacterial solution from the fermenter, bioleach. Test 4: 100% bacterial solution from the fermenter sterilized by the addition of thymol, abiotic. Test 5: 100% pure ferric sulphate solution, abiotic inductively coupled plasma atomic emission spectrometer) following filtration of the slurry samples through filter paper. The presence of Fe(II) was determined by titration with potassium dichromate (Charlot, 1974). The presence of Fe(III) was calculated as a difference between total and Fe(II). For the purposes of mass balance, the leached solids were assayed by atomic adsorption spectrometry after pulverization and fusion with sodium peroxide.

An environmental scanning electron microscope (ESEM) with a coupled X-ray dispersion energy probe, an X-ray diffraction spectrometer and a reflected light optical microscope were used for phase identification and the morphological characterization of the solid material.

Results and discussions

Characteristics of the solid material

The characterization of the solid material revealed that copper is mainly encountered as a zero-valent form of wire and is often oxidized on the surface (Figure 10.1). Zinc was finely disseminated through the material studied, therefore the ESEM observations could not clearly identify it.

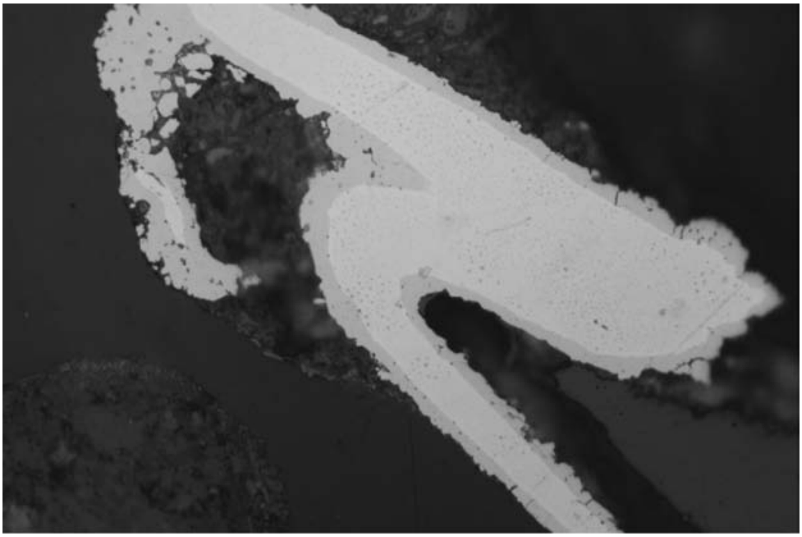

Figure 10.1 Polished section view from the input material indicating copper wire with oxidized parts on its periphery

Please see page 189 for a colour version of this figure.

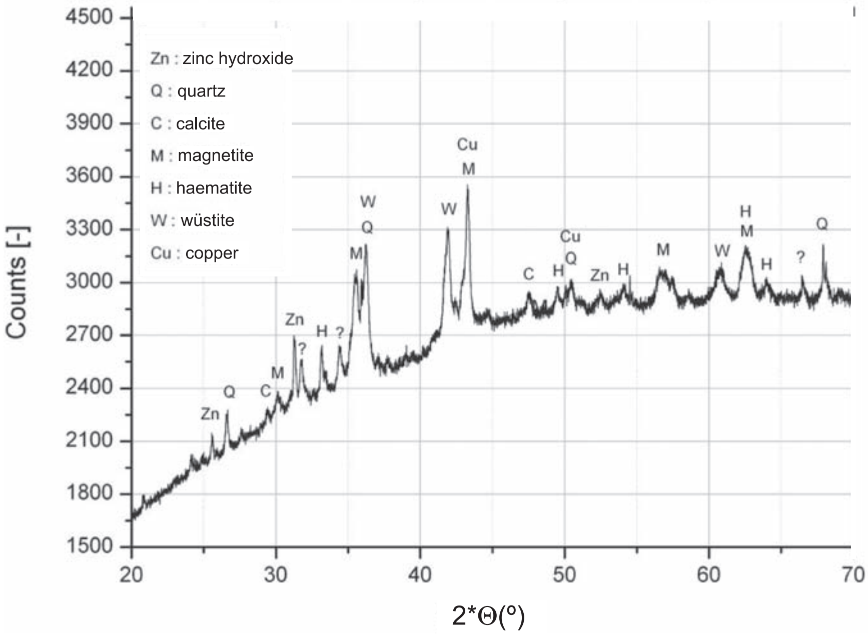

Figure 10.2 X-ray diffraction pattern of the input concentrate

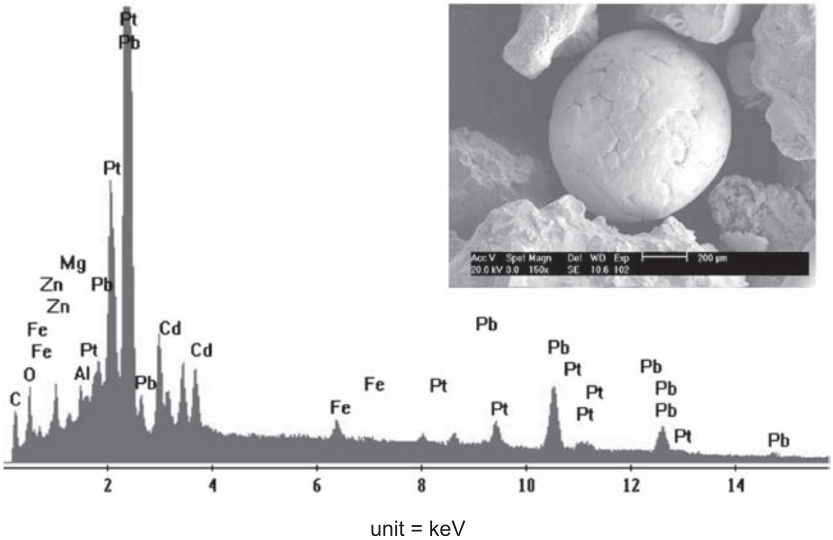

Figure 10.3 Semi-quantitative X-ray dispersive chemical analysis of lead-bearing spheres. Al, aluminium; C, carbon ; Cd, cadmium; Fe, iron; O, oxygen; Mg, magnesium; Pb, lead; Pt, platinum

Please see page 189 for a colour version of this figure.

The X-ray diffraction spectrum shown in Figure 10.2 indicates peaks identifiable as zinc hydroxide or zinc carbonate. Iron occurs mainly in form of oxidized minerals such as haematite (Fe_2O_3), magnetite (Fe_2O_3) and wüstite (FeO). Lead was present in mm-sized spheres composed of a lead, zinc and cadmium alloy most probably formed in the catalytic cracking reactor once the lead melting point temperature was exceeded (Figure 10.3). Gangue was present in the glass and minerals like calcium and magnesium carbonates as well as iron oxides. All the above-mentioned components were identified by the X-ray diffraction analysis, with the exception of glass, as it was in an amorphous phase. Sulphur was not detected.

Effects of bacteria insertion on copper leaching efficiency

The catalytic effect on the iron oxidation rate due to the presence of the bacterial consortium is depicted in Figure 10.4. The results show that, in the absence of suspended solid material, a relatively high rate of oxidation reaching 0.21 g of FeO/L/hour could be achieved. Figure 10.5 presents the evolution of the iron concentration, presented as ferric and ferrous ions, during the leaching tests. A fast consumption or reduction of ferric iron could be observed in the early stage of all the leaching tests. This can

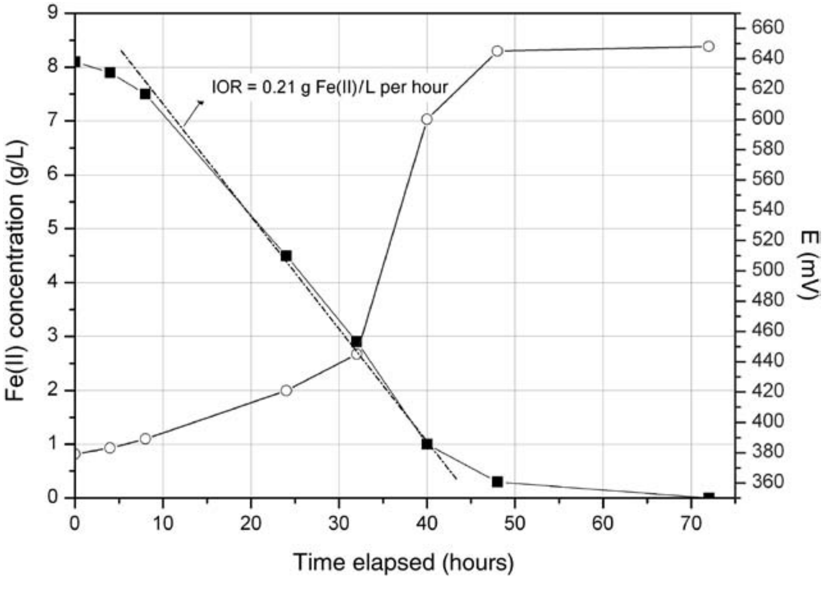

Figure 10.4 Change in ferrous ion (Fe[II]) concentration and redox potential with time and estimation of iron oxidation rate (IOR)

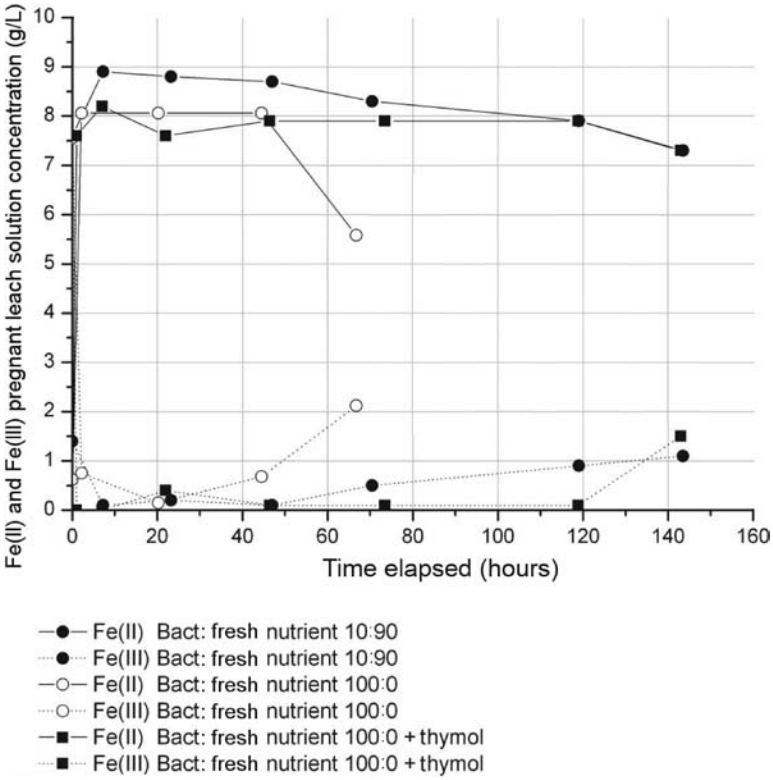

Figure 10.5 Evolution of iron oxide Fe(II) and Fe(III) concentrations in leaching process; tests 2–4

be attributed to the chemical interactions between the ferric iron and zero-valent copper or lead components (the oxidoreductive reactions).

Throughout the duration of the leaching process, the concentration of ferrous iron remained high (Figure 10.5) suggesting a lower regeneration rate of iron compared to the metal solubilization rate. Once the copper leaching began to diminish, a conversion of ferrous to ferric iron started to appear. However, this did not occur not to the full extent but only partially, which does not completely confirm the observations made by Choi et al. (2004). Ferrous iron regeneration mainly occurs under bacterial oxidation. A significant part of the ferrous ion remained in solution after the elapse of the leaching. Distinct evolutions of ferric ion concentrations were observed when bacteria were present in the leaching system. The regeneration of ferrous to ferric iron appeared earlier when living microorganisms were present (tests 2 and 3) while ferric regeneration was absent during most of the sterile test (test 4).

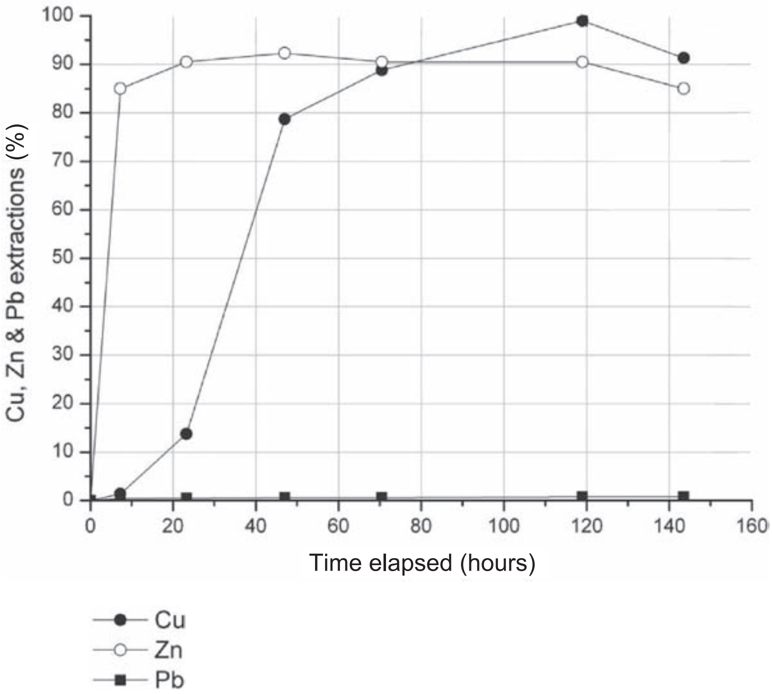

Figure 10.6 Solubilization degree of copper (Cu), zinc (Zn) and lead (Pb) as function of leach time: test 2. Cu, copper; Pb, lead; zn, zinc

The results shown in Figure 10.6 indicate that a high recovery of zinc and copper was achieved in all the leaching tests irrespective of the type of solution used. Zinc proved to be highly soluble in an acidic medium, with more than 90 per cent becoming soluble within the first few hours of leaching. It seems that zinc solubilization does not require the presence of an oxidizing agent, unlike copper. This may be explained by the fact that zinc occurs in mineral phases like zinc hydroxides or zinc carbonate-hydroxides, which are highly soluble in acidic media.

The dissolution of zero-valent copper under the system studied reached high levels of extraction (above 90%) but took more time, as reported elsewhere (Ilyas et al. 2007; Tao et al. 2009). For this dissolution 4–5 days are usually needed. Copper leaching occurred only via oxidoreductive reactions in the presence of an oxidizing agent and leaching is probably directly catalysed by the presence of microorganisms. It should be noted that, in contrast to what has been observed by other authors (Choi et al. 2004), no copper precipitation occurred in our case. Most of the iron

Table 10.5 Metal extraction efficiency during bioleaching and chemical leaching

	Metal extraction (%)				K_{Cu}	Leaching time to recover (hours)		Acid consumption
Test	Cu	Zn	Pb	Fe	(mg/L per hour)	50% Cu	80% Cu	(g/g Cu)
1	0.2	90.0	0.6	54.5	2	–	–	–
2	91.3	85.0	0.8	ND	215	36	50	4.8
3	99.3	97.9	0.6	ND	151	34	81	5.8
4	98.6	94.5	0.5	19.6	76	25	67	5.8
5	94.8	85.2	2.5	ND	98	22	47	4.2

Cu, copper; Fe, iron; KCu, leaching speed of copper, ND, no data; Pb, lead; Zn, zinc.

minerals were solubilized under acidic conditions without an oxidizing agent (test 1).

Lead proved to be non-soluble under the non-oxidizing acidic conditions studied. The addition of an oxidizing agent such as ferric iron allowed its solubilization as lead sulphate but, given the low solubility of lead sulphates, it precipitated immediately as a white precipitate and thus remained in the leach residue with other less soluble metals (such as tin, antimony and precious metals). A similar phenomenon has been reported by other authors (Ilyas et al. 2007).

During leaching, the addition of acid was necessary to control pH at the predetermined value of 1.9. High acid consumption, ranging from 4 to 6 g/g of copper leached were calculated (Table 10.5). The variability in acid consumption was not correlated with the presence of microorganisms but can be explained by slight changes in the mineral composition of the concentrate or the hydrolysis processes that occurs during leaching.

Microorganisms speciation and population dynamics

During the first 24 hours of leaching, a bacterial growth phase was observed independently of culture type. This phase can be identified as the so-called log-phase or growth phase, which corresponds to a rise in the bacterial population. The *L. ferrooxidans* strain showed the highest growth rate, reaching ~10^3 living cells in the stationary phase. Subsequently, the population numbers stabilized at their maximum level depending on the nature of nutrients available (the stationary phase). The thiooxidans strain stabilized at a low level, about 10^2 cells/cc, as the substratum does not provide the reduced sulphur matter required for its growth (such as thiosulphates and sulphides). The population of the *ferrooxidans* genera stabilized at the highest level, reaching about 108 cells/cc for thiobacillus and leptospirillum in total. The number of *T. ferrooxidans* remained high throughout the leaching process, while leptospirillum decreased sharply before the completion of copper leaching. The pH level at which both *L. ferrooxidans* and *T. ferrooxidans* grow at an optimum rate is quite similar. The selected nutrient medium (9K Lundgren–Silverman) is recommended for the growth of *T. ferrooxidans* while the Mackintosh medium is used to stimulate the growth of the *L. ferrooxidans*. This can explain the diminution of the *L. ferrooxidans* population during bacterial leaching in solutions containing the 9K medium.

The comparison of the results from the leaching in the presence of living and non-living bacteria and without the addition of bacteria was carried out by calculating the copper leaching rate, the log-phase duration and the final copper extraction. The results shown in Figure 10.7 clearly illustrate the influence of bacteria on the copper dissolution rate; the latter being strongly enhanced due to bacterial catalytic action, (98 mg/L

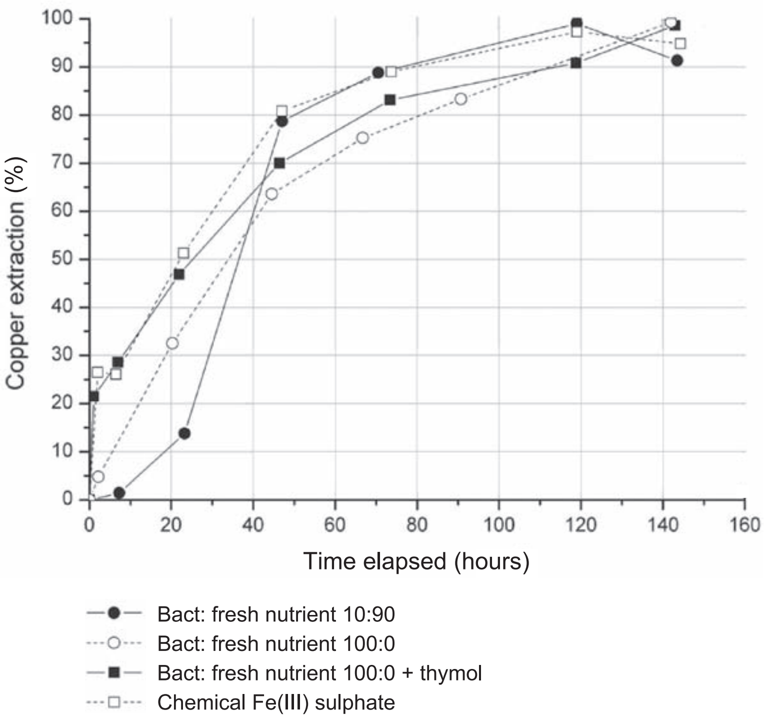

Figure 10.7 Influence of initial leach solution composition on kinetics of copper leaching

per hour without bacteria and up to 215 mg/L per hour when bacteria were present in their log-phase) (Table 10.5). These rates are considerably higher than those reported in the literature (Ilyas et al. 2007).

When comparing the data shown in Table 10.5 and Figure 10.4, we see that the rate of ferric iron regeneration (0.21 g/L per hour) does not correspond to the rate of copper leaching (0.215 g/L per hour). This observation suggests the existence of alternative copper leaching mechanisms that could occur either through the direct action of bacteria or through the action of another oxidizing agent such as cupric cations (Hyvärinen and Hämäläinen, 2004) or dissolved oxygen, via indirect (the regeneration of ferric iron) or direct mechanisms (the direct oxidation of copper).

Conclusions and perspectives

Bio-hydrometallurgical recovery of copper from metal-bearing solid waste has proved to be feasible under the conditions investigated. The different behaviour of the various base metals present in the concentrate (copper, zinc and iron) subjected to leaching was observed. Zinc proved to be very soluble in an acidic medium, while the dissolution of copper required the presence of an oxidizing agent. The poor solubility of lead sulphates was confirmed. The difference in the leaching behavior of copper, zinc and lead suggests the possibility of their selective recovery. Although this is not discussed in the present study, under the experimental conditions studied most precious metals should remain largely in the solid leach residue. Therefore, their subsequent recovery from the cake after the separation of solids from liquids should be investigated. Iron-bearing minerals could be viewed as one of the main acid-consuming impurities. The iron concentration in the input concentrate could be significantly reduced by means of magnetic separation; an operation that would eventually yield a marketable iron concentrate.

The catalytic effect of mesophilic acidophile microorganisms on copper leaching was proved. The presence of thiobacillus and leptospirillum genera appears particularly useful in terms of their ability to significantly enhance the kinetics of copper extraction. The results from pure chemical leaching in which ferric cations are stoichiometrically deficient towards leachable copper have suggested that alternative pathways may be involved in copper leaching. Moreover, the different groups of microorganisms have shown distinctive behavior during bacterial leaching. Future studies will focus on shortening the bacteria lag phase, which will reflect faster leaching kinetics. Alternative nutrient media will be also investigated in order to optimize bacterial population activity in leaching.

Acknowledgements

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11

Influence of ferrous iron supplementation on the bioleaching of copper from printed circuit boards

Luciana Harue Yamane, Denise Crocce Romano Espinosa and Jorge Alberto Soares Tenório

Introduction

Waste of electric and electronic equipment (WEEE) is generated by discarding equipment such as obsolete computers and cell phones, which is stimulated by technology innovations. WEEE has been growing each year. Because of the amount of WEEE that has accumulated it has become a prominent problem but also can be a source of valuable materials, such precious and base metals (Guo et al. 2009; Veit et al. 2006).

Printed circuit boards are generally composed of polymers, ceramics and metals and are found in almost all electric and electronic equipment. Precious metals are used in these circuit boards to avoid the oxidation of base metals and because of their conducting properties (Tenório et al. 1997). The heterogeneous composition and range of metal concentrations in printed circuit boards is a further limiting factor in the recycling processes. Guo et al. (2009) and Veit et al. (2006) report that printed circuit boards can be mechanically processed through size reduction and magnetic separation to concentrate the metals.

The conventional recycling processes are hydrometallurgical and pyrometallurgical; however bioleaching may be an alternative method for recovering base (Choi et al. 2004; Ilyas et al. 2007; Yang et al. 2009) and precious metals (Brandl and Faramarzi 2006) from WEEE. Bioleaching works at room temperature and normal atmospheric pressure, which reduces the energy cost of the process and avoids the emission of gas

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Solving the e-waste problem: an interdisciplinary compilation of international e-waste research, Khetriwal, Luepschen and Kuehr (eds),
United Nations University Press, 2013, ISBN 978-92-808-8035-9

pollutants (Mousavi et al. 2006). Bioleaching experiments can use percolation columns, leaching columns, shake flasks and bioreactors (Olson et al. 2003).

Advances in knowledge of bioleaching as an economically viable process to recover metals are also attributed to the depletion of high grade ores (Valdívia and Chaves 2001). Today, bioleaching is applied on a commercial scale for the recovery of copper and uranium from low level ores and sulphide minerals (Garcia et al. 2007; Sepulveda et al. 2010). Studies (Brandl and Faramarzi 2006; Olson et al. 2003; Valdívia and Chaves 2001) describing bacterial leaching for metal extraction (e.g. copper) as a pretreatment for the subsequent recovery of precious metals have been reported.

Bacterial adaptation is the first step of the bioleaching process in which the bacteria come in contact with waste or ore through several subculturing steps. The adaptation process can be done by a gradual decrease of ferrous hydroxide (Fe^{+2}) and a gradual increase of substrate concentration, but no protocol or predefined conditions exist for such adaptation periods, pulp densities and inhibitory metal ion concentrations (Bevilaqua et al. 2002; Haghshenas et al. 2009).

According to Nemati et al. (1998), bacteria are able to produce spontaneous phenotypical variants under different environmental conditions due to the transposition of mobile DNA sequences. The adapted bacteria can adhere more easily to mineral surfaces as more proteins on the surface of the cell can engage in specific interactions with minerals (Xia et al, 2008). Other events, such as an increase of the suspended bacterial population, the decrease of bacterial tolerance to solids and ruptures of the cell membrane and the increase of the cells' ability to degrade the sulphur layer (Haghshenas et al. 2009) might explain what happens during the adaptation process.

Studies using thermophilic and mesophilic bacteria (Brandl et al. 2001; Choi et al. 2004; Ilyas et al. 2007; Wang et al. 2009; Yang et al. 2009) have demonstrated that metals can be recovered from printed circuit board scrap by bacterial leaching. Choi et al. (2004), Ilyas et al. (2007) and Yang et al. (2009) studied the recovery of copper of from printed circuit boards in shake flasks, achieving copper extraction rates higher than 70 per cent.

The aim of this work was to investigate the influence of Fe^{+2} supplementation on the bioleaching process to recover copper from the nonmagnetic fraction of the printed circuit boards of obsolete computers using adapted *Acidithiobacillus ferrooxidans* LR bacterium.

Materials and methods

Printed circuit boards

Printed circuit boards from obsolete computers were comminuted (< 2 mm) in a hammer mill and placed in a magnetic cross-belt separator. Samples obtained through separating the non-magnetic fraction in the magnetic separator were used in the bioleaching experiments and chemical analyses.

Organisms and culture conditions

The bacterium *A. ferrooxidans* strain LR, isolated from uranium mine effluents, (Garcia 1991) was used in this work. A T&K medium that was adopted for the growth of bacterial inoculum (Tuovinen and Kelly 1973) was composed of solutions A and B. Solution A contained ammonium sulphate $(NH4)_2SO_4)$, 0.625 g/L^{-1}; hydrated magnesium sulfate ($MgSO_4.7H_2O$), 0.625 g/L^{-1}; and dipotassium phosphate (K_2HPO_4), 0.625 g/L^{-1} and solution B contained ferrous sulfate heptahydrate ($FeSO_4.7H_2O$) 166.5 g/L^{-1}.

For the preparation of the T&K medium, solutions A and B were prepared, acidified with sulphuric acid 10N to 1.8 pH and sterilized separately. Solution A was sterilized by autoclaving at 120°C for 30 min and 1 atm. Solution B was filter sterilized (0.45 µm). Finally, solutions A and B were mixed in the proportion 4:1.

Bacterial adaptation process

A. ferrooxidans LR was initially adapted through several subcultures with a gradual increase of the concentration of printed circuit boards (non-magnetic fraction samples) and a gradual decrease of Fe^{+2}. The bacteria grew in 200 mL of the T&K medium in sterilized flasks (250 mL) with sample concentrations of printed circuit boards (non-magnetic fraction) ranging from 2.5 to 15 gL^{-1} at 30°C and 185 rpm.

Bioleaching experiments

Shake flasks experiments were carried out in 250 mL Erlenmeyer flasks (sterilized by autoclaving) containing 200 mL of the culture medium. In total 15 gL^{-1} of printed circuit board samples was added to each flask under sterile conditions. The flasks were inoculated with 5 per cent (v/v) inoculum of *A. ferrooxidans* LR, weighed and incubated at 185 rpm and 30°C ± 2°C.

The bioleaching experiments were performed in triplicate and the water lost by evaporation was replenished at each sampling with acidic sterile water (pH 1.8) and the pH culture medium was adjusted with sulphuric acid 10N to 1.8–2.0. The parameters evaluated were the pH and the ferrous iron concentration.

Bacterial adaptation experiment

The aim of this experiment was to evaluate the influence of bacterial adaptation on copper bioleaching from the non-magnetic fraction of printed circuit boards. The process of bacterial adaptation was conducted through several subcultures with a gradual increase of the concentration of printed circuit board (non-magnetic fraction) until 15 gL^{-1} was obtained. Shake flask experiments were inoculated with adapted and non-adapted *A. ferrooxidans* LR. An uninoculated control was conducted in parallel.

Influence of Fe^{+2} initial concentrations

The aim of these experiments was to investigate the influence of Fe^{+2} initial concentration on bioleaching process to recover copper from non-magnetic fraction of printed circuit boards using adapted *A. ferrooxidans* LR bacteria. Two conditions were evaluated. In the first a bioleaching experiment was carried out using a T&K medium completely inoculated with adapted bacteria and in the second the experiment was performed with solution A (the culture medium without ferrous iron) inoculated with adapted bacteria. Uninoculated control conditions were also conducted in parallel.

Analytical methods

To determine the initial metal concentration in the non-magnetic fraction of the printed circuit boards, the sample was dissolved in nitro-hydrochloric acid in the proportion 1:20 (Park and Fray 2009) (1 g of printed circuit board sample to 20 mL of nitro-hydrochloric acid solution). Contact between the printed circuit board waste and nitro-hydrochloric acid continued for 24 hours followed by simple filtration with quantitative filter paper. The leached fraction was analysed by inductively coupled plasma optical emission spectrometry (ICP-OES).

For measurements of pH, a bench pH meter was used (an Ag^0/silver chloride reference). Leach liquor samples were periodically withdrawn for chemical analyses (1, 2, 3, 4, 5, 6, 7, 10, 15, 20, 30, 40 days) and centrifuged for 20 min at 5000 rpm. 10 mL from the supernatants was used to determine the Fe^{+2} concentration and 5 mL was preserved with 1 mL nitric acid concentrate at 4°C for copper (Cu) and total iron (Fe) analyses. The copper and Fe total concentrations were determine by ICP-OES.

The determination of the Fe^{+2} concentrations was performed by titration with potassium dichromate ($K_2Cr_2O_7$). 10 mL samples were acidified with 20 mL acid mixture (sulphuric acid: phosphoric acid; H_2SO_4/H_3PO_4) and diluted to 50 mL. After this, 3 drops of indicator (1% barium diphenylamine sulfonate) were added and the solution was titrated with potassium dichromate until it turned from green to purple. Fe^{+2} concentrations were calculated by the consumption of potassium dichromate solution, based on reaction 1:

$$Cr_2O_7 - 2 + 6Fe^{+2} = 14H+ \rightarrow 2Cr^{+3} + 6\ Fe^{+3} + H_2O \quad (1)$$

Fe^{+3} concentrations were calculated through difference between Fe total and Fe^{+2} concentrations. The initial copper concentration (CC) was used to calculate the copper extraction rate using equation 1:

$$\%\ \text{extraction of copper} = ([\text{Initial CC} - \text{Leach CC}]/\ \text{Initial CC}) \times 100 \quad (1)$$

The leach copper concentration (leach CC) was determined in the leach liquor samples taken from bioleaching experiments.

Results and discussion

Printed circuit boards

Samples of the non-magnetic fraction (82% w/w) of printed circuit boards were used in this study. Copper was the metal that presented the highest concentration (18.3% w/w). The chemical analyses (%w/w) of this fraction are shown in Table 1.

The non-magnetic fraction of the printed circuit boards consists of around 40 w/% metals and 42 w/% other materials (ceramics and polymers). Copper is present in the highest percentage of metals in the printed

Table 11.1 Composition (% w/w) of non-magnetic fraction of printed circuit boards

Metals analysed by inductively coupled plasma optical emission spectrometry									Polymers and ceramics
Cu	Sn	Pb	Al	Zn	Fe	Ni	Ag	Au	
18.3	7.8	4.9	4.5	3.9	0.4	0.2	0.1	0.1	41.8

Cu, copper; Sn, tin; Pb, lead; Al, aluminium; Zn, zinc; Fe, iron; Ni, nickel; Ag, silver; Au, gold.

circuit boards studied. This is because computer printed circuit boards are of type FR-2, which has a layer of paper impregnated with a plasticized phenol formaldehyde resin with copper foil lamination on one or both sides. The surface contains a copper layer to connect the electrical contacts. Small amounts (0.2% w/w) of precious metals were also present.

Studies by Park and Fray (2009), Tenório et al. (1997) and Veit et al. (2006) demonstrate that the composition of printed circuit boards changes probably due to different methodologies applied in the studies or because the composition has changed over time. Ilyas et al. (2007) also suggest that this difference can be attributed to the analytical methods used and the origin of the material.

Bioleaching experiments

Bacterial adaptation experiment

In bioleaching studies using adaptation of microorganisms (Haghshenas et al. 2009; Horta et al. 2009; Ilyas et al. 2007; Li and Ke 2001; Xia et al. 2008) results showed that the recovery rates of metals by adapted bacteria were superior compared to the recovery rates achieved with non-adapted bacteria.

Xia et al. (2008) observed that the adapted bacteria increased the dissolution rate of copper compared to unadapted bacteria in a study of chalcopyrite bioleaching using *A. ferrooxidans.* This suggests that there are significant differences in the attachment and tolerance of the bacteria to the shearing stress of adapted and unadapted cells due to changes in the components and the structure of the cell wall.

In this initial copper bioleaching study, the bacterial adaptation process was performed to adapt *A. ferrooxidans* LR until 15 gL^{-1} was attained. Results obtained in copper extraction (Figure 11.1) with adapted bacteria show that after 30 days the copper bioleaching rate by adapted bacteria was 13 per cent higher than by unadapted bacteria. In the inoculated flasks (Figure 11.1) extraction was higher in the first 7 days, probably due to the bacterial growth being in the exponential phase. Consequently, the exponential increase of the bacterial cells caused an increase of bacterial metabolic activity involving ferrous iron oxidation to Fe^{+3} and copper solubilization.

After day 8 bacterial growth entered the stationary phase and the copper extraction rate decreased because, at this stage, the number of bacterial cells remained constant until the death phase. The unadapted bacteria and the uninoculated control condition reached a lower extraction rate, showing that in these conditions the bacterial activity was inhibited and

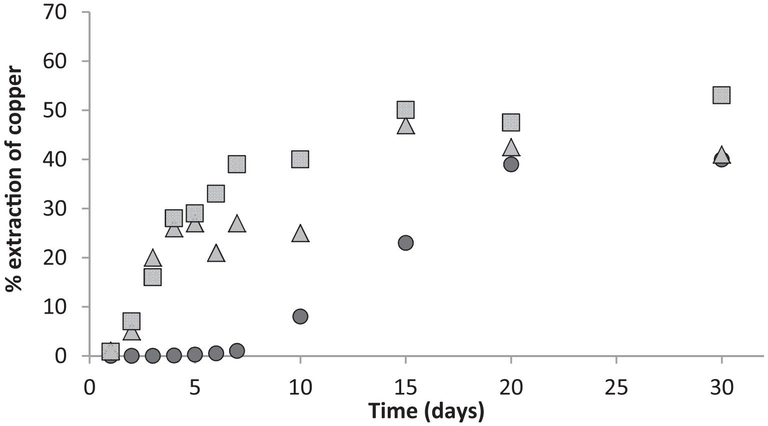

Figure 11.1 Copper extraction rate over time, showing (●) abiotic control; (■) adapted *A. ferrooxidans* LR growing with 15g L^{-1} non-magnetic fraction; (▲) *A. ferrooxidans* LR unadapted growing with 15g L^{-1} non-magnetic fraction

copper leaching was probably only chemical. According to Nemati et al. (1998), natural populations of *A. ferrooxidans* are resistant to copper ions (1–2 gL^{-1}) and bacterial activity can be inhibited by higher concentrations ranging between 0.45 – 4.45 gL^{-1} but adapted strains can tolerate concentrations up to 29.8 gL^{-1} copper ions. Bacterial adaptation decreased the *A. ferrooxidans* LR sensitivity to generated copper ions, which increased the copper bioleaching rate.

Influence of initial concentrations of Fe^{+2}

The results in Figure 11.2 show that the copper extraction rate with the complete inoculated T&K medium was higher than in the inoculated T&K medium without Fe^{+2} due to the fact that the bacterial direct mechanism is based on the oxidation of Fe^{+2} to Fe^{+3} (Sand et al. 2001), as shown in reaction 1:

$$2Fe^{+2} + \frac{1}{2}\, HO_2 + 2H+ \rightarrow \mathit{A.f.}\ 2Fe^{+3} + H_2O \qquad (1)$$

The ferric ion generated (Equation 1) by *A. ferrooxidans* activity oxidizes metals through the bacterial indirect mechanism (Sharma et al. 2003). Similar results were obtained in studies without the addition of Fe^{+2} in the bioleaching process using shake flasks (Rohwerder et al. 2003; Xia et al. 2008).

Figure 11.2 also shows that the extraction is more pronounced in the first 7 days of the experiment in the inoculated complete T&K medium

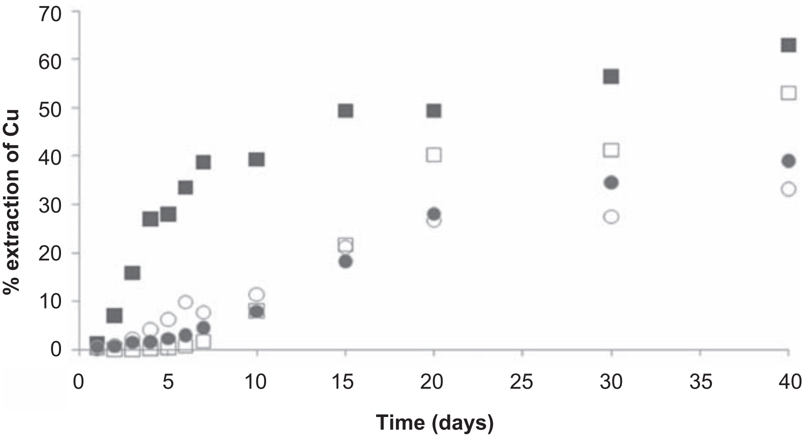

Figure 11.2 Copper (Cu) extraction rate over time, showing (□) abiotic control with complete T&K medium and printed circuit boards; (■) adapted *A. ferrooxidans* LR growing with printed circuit boards in complete T&K medium; (○) abiotic control with T&K medium without Fe^{+2} and printed circuit boards; (●) adapted *A. ferrooxidans* LR growing with printed circuit boards in T&K medium without Fe^{+2}

probably because the bacterial growth is in the exponential phase, resulting in an exponential increase in the number of bacterial cells by increasing bacterial metabolic activity (oxidation of Fe^{+2} to Fe^{+3}) and consequent copper dissolution, as shown in reaction 2:

$$CuO + 2Fe^{+3} \leftrightarrow 2Fe^{+2} + Cu^{+2} \tag{2}$$

From the 8th day bacterial growth in the inoculated complete T&K medium enters in the stationary phase and copper extraction becomes less intense because, at this stage, the number of bacterial cells remains constant until the death phase. Using the complete T&K medium, the bacteria leached about 60 per cent more than in the medium without ferrous iron supplementation. A similar result was obtained by Bevilaqua et al. (2002) in the bio-oxidation of chalcopyrite, in which the culture of *A. ferrooxidans* with additional iron leached twice as much copper as in a culture without additional iron. Furthermore, the non-magnetic fraction of printed circuit boards did not have a high iron concentration (0.4% w/w), therefore the largest source of iron for the bacteria was the solution of ferrous sulphate (solution B of the T&K medium).

Solution A (both control and inoculated) showed a less than 40 per cent copper extraction. Although copper is insoluble in dilute sulphuric acid, aeration of the medium introduces oxygen in the solution which can promote solubilization (Mendham et al. 1989).

The bacterium *A. ferrooxidans (A.f.)* is chemolithotrophic with CO_2 as a carbon source for growth. The medium must be agitated in order to provide aeration (Nemati et al. 1998). Even without iron the medium solubility of copper occurred, probably as a result of being shaken (185 rpm), which favoured the chemical leaching of copper. Thus, a decrease in agitation could be used to suppress the effect of chemical leaching. Bioleaching studies (Brandl et al. 2001; Choi et al. 2004; Ilyas et al. 2007; Wang et al. 2009; Yang et al. 2009) report extraction rates above 70 per cent under conditions of agitation between 150 rpm and 250 rpm.

The results obtained in the inoculated solution A showed that bacterial activity did not significantly increase the extraction of copper ($< 5\%$) compared with the control in the same condition, indicating that the copper was primarily solubilized by chemical leaching. Figure 11.3 shows the changes in pH before adjustments to it from 1.8 to 2.0. pH stability is needed because CO_2 is a limiting factor in bacterial growth and acid pH is fundamental in the solubility of CO_2 (Nemati et al. 1998).

In the inoculated T&K medium without Fe^{+2}, the pH increased (to above 3.5) until day 15, suggesting acid consumption during the oxidation of other metals from printed circuit boards, such as zinc, tin, aluminium, lead and copper. pH values lower than 1.3 or greater than 3.5 strongly inhibit bacterial growth (Nemati et al. 1998), which probably inhibited

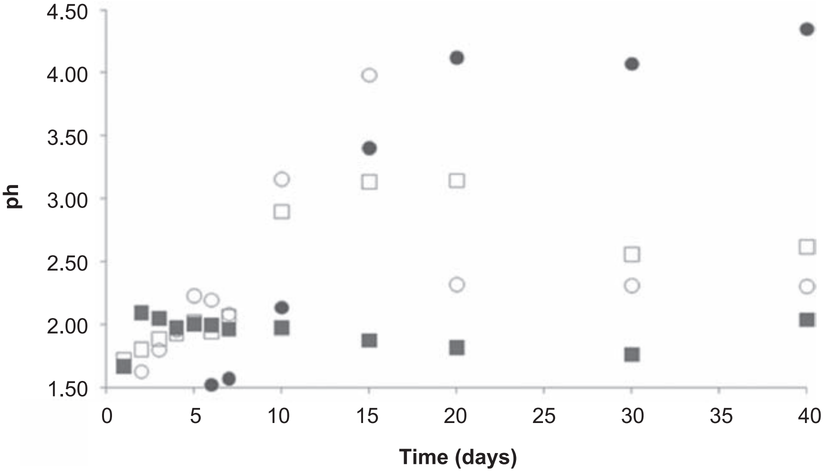

Figure 11.3 pH before adjustment over time, showing (□) abiotic control with complete T&K medium and printed circuit boards; (■) adapted *A. ferrooxidans*-LR growing with printed circuit boards in complete T&K medium; (○) abiotic control with T&K medium without Fe^{+2} and printed circuit boards; (●) adapted *A. ferrooxidans*-LR growing with printed circuit boards in T&K medium without Fe^{+2}

the bacterial activity after day 20 of the experiment, corroborating the fact that the rate of copper extraction obtained in the inoculated medium without Fe^{+2} was not affected by bacterial activity.

In the control condition without Fe^{+2}, the maximum rate of extraction obtained was about 30 per cent. pH increased until day 15, showing the consumption of acid during the chemical leaching of metals from printed circuit boards. Another factor that could explain the higher pH values of the control condition even with the adjustments is the acid (H+) consumption was not reset through the Fe^{+2} to Fe^{+3} cycle. After 25 days the extraction of copper did not increase and the extraction of copper reached its maximum value.

The pH of the inoculated complete T&K medium remained steady between 1.8 and 2.0 after day 8, possibly due to the combinations of reactions that consume acid, such as the chemical and microbiological oxidation of Fe^{+2} and the reactions that produce acid, like the hydrolysis of ferric ion (Ilyas et al. 2007; Yang et al. 2009). The pH of the control complete T&K medium presented values higher than that of the inoculated medium (Figure 11.3), probably because of the consumption of H+ and O_2 (promoted by shaking) in Fe^{+2} oxidation. This also explains the copper leaching rate in the control complete T&K medium (Figure 11.2) by the Fe^{+3} From day 25 the extraction of copper reached its maximum value.

After day 20 a decrease in pH was observed in the complete T&K medium (control) probably because of the precipitation of jarosite, which produces acid. The formation of jarosite was observed in the wall of the flasks after day 20. The general formula of jarosite is $MFe_3(SO4)_2(OH)_6$, where M = K^+, Na^+, $NH4^+$ or H_3O^+, which is a reaction that produces acid (Nemati et al. 1998).

Figure 11.4 presents the results of changes in Fe^{+2} concentrations. The ferrous iron concentrations obtained in the T&K medium without Fe^{+2} (control and inoculated) were negligible.

In the inoculated complete T&K medium, it was observed that Fe^{+2} was consumed until the day 10, indicating the exponential phase of the bacterial growth. Bevilaqua et al. (2002) observed the same behaviour in chalcopyrite bioleaching. Nemati et al. (1998) concluded that the ferrous iron concentration has a strong influence on bacterial growth, consequently this parameter is often used as a way to monitor the growth rate by observing the decline in growth resulting from the depletion of ferrous ion in the substrate. However, high concentrations ranging from 2–6g L^{-1} can have an inhibitory effect. In a copper recovery study from printed circuit boards using *A. ferrooxidans*, Choi et al. (2004) concluded that the addition of ferrous ion to the bioleaching process helps to promote copper dissolution.

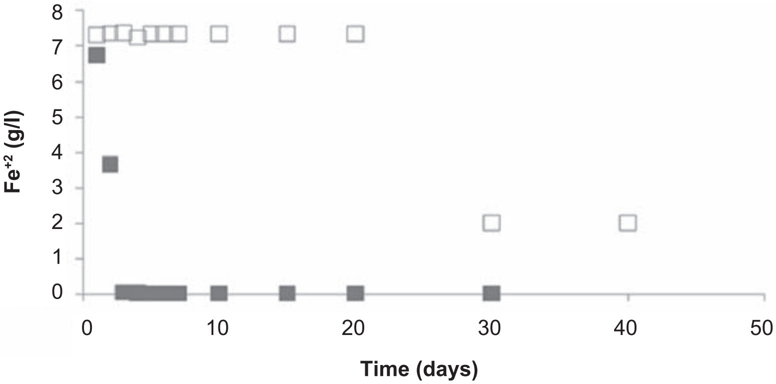

Figure 11.4 Changes in Fe^{+2} concentrations over time, showing (□) abiotic control with complete T&K medium and printed circuit boards; (■) adapted *A. ferrooxidans* LR growing with printed circuit boards in complete T&K medium

In the control complete T&K medium, the Fe^{+2} concentrations started to decline after the day 20 (Figure 11.4). Similar behaviour was observed by Francisco et al. (2007) in the bacterial leaching of a complex mineral sample containing pyrite, pyrrhotite and molybdenum, which suggested that this may have occurred through the natural oxidation of Fe^{+2}.

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Figure 4.1 E-waste disposal with municipal solid waste

Please see page 75 for this figure's placement in the text.

Figure 4.2 Material recovery from selected components is taking place

Please see page 76 for this figure's placement in the text.

Figure 4.3 Material recovery from selected components is also taking place

Please see page 77 for this figure's placement in the text.

Figure 6.2 E-waste in the municipal dump (Source: photograph taken by researchers during the data collection)

Please see page 105 for this figure's placement in the text.

Figure 6.3 E-waste burning together with other municipal waste (Source: photograph taken by researchers during the data collection)

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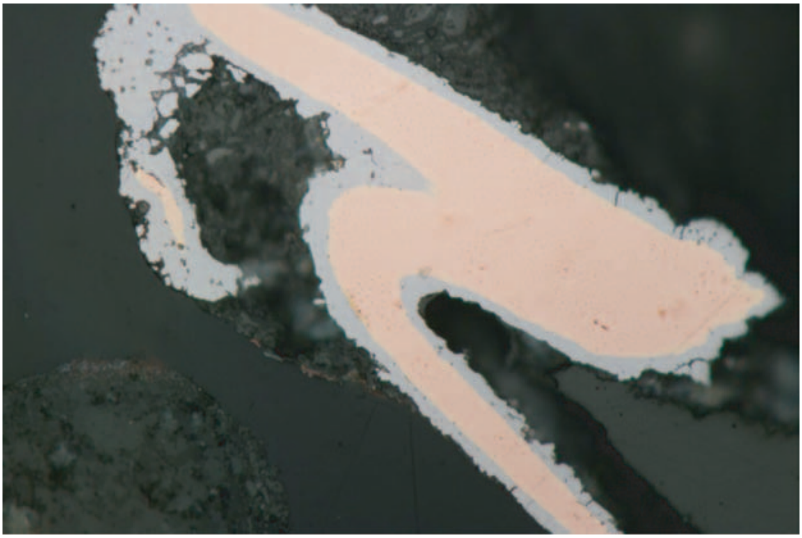

Figure 10.1 Polished section view from the input material indicating copper wire with oxidized parts on its periphery

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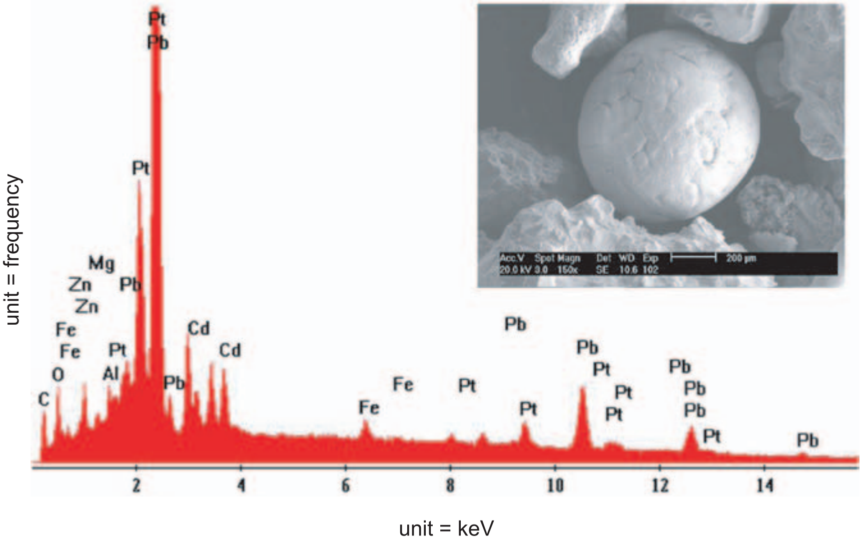

Figure 10.3 Semi-quantitative X-ray dispersive chemical analysis of lead-bearing spheres. Al, aluminium; C, carbon ; Cd, cadmium; Fe, iron; O, oxygen; Mg, magnesium; Pb, lead; Pt, platinum

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