TOWARDS USE OF BIODEGRADABLE MATERIALS AS ELECTRO-COMPONENTS

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ABSTRACT

The rapid growth in the ICT sector has led to an improvement in capacity of e-devices and the rate of discarded electro-devices is at an alarming rate, especially in nations where markets are flooded with huge quantities of innovative electrical and electronic equipment (EEE). This phenomenal growth has resulted an increase in the amounts of discarded waste which is obvious in Nigeria and other parts of the world. It is estimated that Nigeria generates 1.1M tonne of e-waste annually. 75% of used-EEE are stored due to uncertainty of how to manage such items. These leftovers, containing hazardous inorganic components, lie unattended and normally mixed with domestic solid wastes. This is owing to inadequate planning and appraisal of management functions of emerging wastes. Nations are now embracing rethinking strategies for managing e-waste and optimizing finite resources.

Components of e-devices are chiefly made-up of valuable inorganic metals, glassware/ceramics and thermoplastics. In personal computers (PCs), 26% of its content is made-up of silica/glass, while plastic occupy 23%. Metals constitutes approximately 50% of PCs. These metals are used in circuit-boards, conducting wire and body-casing for EEE. Plastics are chiefly used in wire-coating and casing for components of e-devices. They normally biodegrade very slowly, with full degradation occurring after 500 or 1000 years. Whereas glassware/ceramics are employed in production of transistors, valves, diodes and LED components.

An increase interest in cheap disposable and eco-friendly devices has focused research towards the development and adaptation of low-cost electronic sensing devices. This paper review the rising trends of WEEE, recent developments in new technologies for production of e-components with tendency of biocompatible and biodegradable at their E.o.L, as well as suggest policy direction toward applying new technology frontiers like OFETs, OTFTs, OLEDs, and OPVs in the manufacturing of electro-devices as alternative over comparable inorganic devices in the production of electro-components.

Keywords: WEEE/E-waste, Environmental-Sound-Management (ESM), Recycling, Biodegradable E-waste, E-device

INTRODUCTION

Access to Information and Communication Technology (ICT) has been identified as an indicator of a country's economic and social development (UN, 2011). Thus, the rapid growth in the ICT sector has led to an improvement in capacity of electrical and electronic equipment (EEE) but simultaneously to a decrease in products' lifetime, such that the volume of waste generated is increasing by 10% annually (Oh *et al*., 2003; Ayodeji, 2011). Many countries, however, lack the infrastructure and resources for an environmentally sound management (ESM) of waste from EEE (e-waste) arising when such imports reach their end-of-life (E.o.L). Some West Africa countries including Côte d'Ivoire, Liberia, Ghana, Benin and Nigeria, are now facing huge challenges in the management of Waste Electrical and Electronic Equipment (WEEE) which are either locally generated or imported illegally as "second hand" goods (Basel Convention, 2011a). Research have shown that most used EEE consignments imported into developing countries are mixtures of less than 25% of used functional EEE and over 75% of WEEE (BCCCN Report, 2011; NESREA, 2011). Even the so called functional products are near their E.o.L, which so many of such countries have the challenge of dealing with.

Public nuisance and health challenges arising from e-waste disposal are of serious concerns to man and the environment. The hazardous constituents present in waste electrical and electronic equipment (WEEE) components render it unsafe when such wastes are dismantled and processed (Osibanjo & Nnorom, 2008; eWASA, 2009; Oliver and Charles, 2010). The exposure to WEEE hazards in and around dismantling sites causes manifold health and safety risks for scavengers, recyclers and neighbouring populations (Basel Convention, 2011a). E-wastes therefore are considered unsafe, because certain components of these products contain materials that are hazardous, depending on their condition and handling at disposal sites (GFMECD, 1995). Hazardous substances are released during various dismantling and disposal operations of WEEE and are particularly severe during the burning of cables to liberate copper and of plastics to reduce waste volumes. For example, certain components of electro-devices leaches heavy metals like lead, mercury, cadmium and other substances into the environment causing acidification of soil and ground-water (NESREA, 2011). Such harmful substances in these components pose threat to both human health and the environment when improperly disposed (Alo, 2009; The Guardian, 2012; Vanguard, 2013).

The processes of managing WEEE stream in many countries with emerging economies, like Nigeria, are not clearly spelt out and practiced. Most of what happens is that individuals, dealers and importers buy these items as fairly-used goods for direct reuse or dismantle to collect components for recycling and discard the remnants along with municipal solid wastes (Osibanjo & Nnorom, 2007). Further health and safety risks originate from the emissions of informal lead acid battery recycling, which is commonly practiced within dismantling sites. Such hazards can have negative impacts on the environment and affect human health if not properly managed as peculiar reoccurrence in many developing countries which lack adequate infrastructure to manage wastes safely (StEP, 2011). At least 734 children below the age of five, out of 5,395 within this age bracket, were confirmed killed from lead poisoning between 2010 and March 2013 in Zamfara State (ThisDay Newspaper, 2013). Therefore, this poses a growing environmental problem.

There is the need for a rethink in the production and usage of EEE through the application of technology frontiers that are environmentally compactable and safe to humans. This review highlights recent advances in new technology frontiers in the use of highly unconventional materials for the production of e-components with tendency of biocompatible and biodegradable at their E.o.L; compare technologies of natural materials for organic electronics as alternative to inorganic e-devices as well as advocate policy direction toward biodegradable EEE development.

CHEMICAL CONSTITUTE IN E-WASTE

Many components of EEE (e-devices) are made-up of valuable metals (like aluminium, copper, lead, cadmium, zinc, mercury, ferrous metals etc.), glassware/ceramics and thermoplastics. In personal computers (PCs), 26% of its content is made-up of silica/glass, while plastic occupy 23%. Metals constitutes approximately 50% of PCs (Oresanya, 2011). These metals are used in circuit-boards, conducting wire and body-casing in EEE. Plastics are chiefly used in wire-coating and casing for components of e-devices. They normally biodegrade very slowly, with full degradation occurring after 500 or 1000 years (Mihai et. al., 2012). Glassware/ceramics are chiefly employed in production of transistors, valves, diodes and LED components.

Generally, WEEE as composite material is not hazardous per se. However, electrical and electronic devices consist of complex mixture of materials and components. Also, some naturally occurring harmless substances become hazardous because of their use in the manufacture of electronic equipment (e.g. chromium becomes chromium VI). EEE are known to be made-up of more than 1000 different substances, many of which are highly toxic (Ongondo and Williams, 2011). Table 1 gives a representation of some components used in the manufacturing of EEE and their relative constitutes.

Table 1: A Selection of the Mostly Found Toxic Substances in WEEE

SUBSTANCE	OCCURRENCE IN E-WASTE
Halogenated compounds:	
- PCB (polychlorinated biphenyls)	Condensers, Transformers
- TBBA (tetrabromo-bisphenol-A) - PBB (polybrominated biphenyls) - PBDE (polybrominated diphenyl ethers)	Fire retardants for plastics (thermoplastic components, cable insulation) TBBA is presently the most widely used flame retardant in printed wiring boards and casings.
- Chlorofluorocarbon (CFC)	Cooling unit, Insulation foam
- PVC (polyvinyl chloride)	Cable insulation
Heavy metals and other metals:	
- Arsenic	Small quantities in the form of gallium arsenide within light emitting diodes
- Barium	Getters in CRT
- Beryllium	Power supply boxes which contain silicon controlled rectifiers and x-ray lenses
- Cadmium	Rechargeable NiCd-batteries, fluorescent layer (CRT screens), printer inks and toners, photocopying-machines (printer drums)

SUBSTANCE	OCCURRENCE IN E-WASTE
- Chromium VI	Data tapes, floppy-disks
- Lead	CRT screens, batteries, printed wiring boards
- Lithium	Li-batteries
- Mercury	Fluorescent lamps that provide backlighting in LCDs, in some alkaline batteries and mercury wetted switches
- Nickel	Rechargeable NiCd-batteries or NiMH-batteries, electron gun in CRT
- Rare Earth elements (Yttrium, Europium)	Fluorescent layer (CRT-screen)
- Selenium	Older photocopying-machines (photo drums)
- Zinc sulphide	Interior of CRT screens, mixed with rare earth metals
Others:	
- Toner Dust	Toner cartridges for laser printers / copiers
Radio-active substances	
- Americium	Medical equipment, fire detectors, active sensing element in smoke detectors

Source: Agency for Toxic Substances and Disease Registry, ATSDR (2013)

RISING TRENDS OF WEEE IN NIGERIA

From the Basel Convention 2011 Report, the penetration rate of personal computers has increased in the last decade by a factor of 10 (Basel Convention, 2011a; Cornelius Tsamo, 2014), while the number of mobile phone subscribers has increased by a factor of 100. The whole world is currently grappling for solutions to the ever increasing generation of WEEE, its movement from developed to developing countries and the associated impact on human health and the environment.

There has been considerable media attention based on a few reports pointing to the trade of used EEE in Nigeria (Puckett *et al*. 2003; NESREA, 2009; The Guardian, 2012). On a daily bases, an estimated 500 containers of used electronics & computers are imported into Lagos Ports (Oresanya, 2011). In the year 2010, an analysis of containers of used EEE for categories 2-4 imported into Nigeria was conducted between the months of May and July monitoring shipment manifests and providing shipping information for about 176 containers (Basel Convention, 2011a). The results revealed that almost 60% of the containers of used EEE came in from the UK, with Felixtowe being the dominant exporting port. More than 75% of all containers came from Europe, approximately 15% from Asia, 5% from African ports (mainly Morocco) and 5% from North America. In the light of this rising trend, the National Environmental Standards and Regulation Enforcement Agency (NESREA) recently ordered an e-waste carrying vessel at the Tin-Can Island Port, (Vanguard, 2013) Lagos to send its consignment back to the port of origin in the United Kingdom sighting the provisions of Harmful Wastes Act, promulgated after the Koko waste saga in 1988. The e-waste ship carried toxic wastes (WEEE) laden containers on board designated for dumping in Nigeria. Hitherto 2011, NESREA had intercepted and arrested five (5) ships carrying e-waste destined for Nigeria (BCCCN Report, 2011).

TECHNOLOGY FRONTIERS: USING BIODEGRADABLE MATERIALS AS ELECTRO-COMPONENT

Many organic materials have been shown to be biodegradable, safe, and nontoxic, (Mihai *et al*, 2012) including compounds of natural origin. Biodegradation is a natural form of recycling. It is the disintegration of carbon to carbon dioxide to the level of 60% (Seigel and Barlow, 2014), over a period of 180 days with the fragments giving non-distinguishable pieces and no evidence of any eco-toxicity in finished compost and soils of which can support plant growth. According to the standard set for biodegradable e-component, such product must meet with certain tests including Biodegrade (be converted to carbon dioxide, water and biomass at same rate as Kraft paper and other certified compostable material); Disintegrate (not be visible or need to be screened out after composting); Be Safe for the Environment (degradation must not cause any harmful by-products and the compost must be able to support plant growth) (Seigel and Barlow, 2014). Biodegradable substances are eco-friendly at their end-of-life (E.o.L).

Until recently, legislations, policy, guidelines and standards are merely directed towards the Control of Transboundary Movements of Hazardous Wastes and their Disposal, Take-back and Extended Producer Responsibility (EPR) programs for end-of-life EEE, (Basel Convention, 2011b; NESREA, 2011). A newer push toward sustainable management of e-waste is the likelihood application of organic field effect transistors (OFETs) Technology, Organic thin-film transistors (OTFTs), organic light emitting diodes (OLEDs), and organic photovoltaics (OPVs) in the manufacturing of electro-devices (Schwabegger *et al*., 2011; Maria *et al*, 2011; Mihai *et al*, 2012). With application of such technologies, biodegradable materials, like carbon nanotubes and graphene sheets, which offers higher performance in terms of field-effect mobility and sensitivity , could be used as alternative to inorganic substances in the manufacturing of high mobility, low voltage operating C60 based n-type organic field effect transistors (Maria *et al*, 2011; Mihai *et al*, 2013); paper substrates (applied as Low-voltage active circuits on banknotes, for anti-counterfeiting applications) (Mihai *et al,* 2012); insulators, semiconductors and conductors for electrical and electronic devices.

Several research works conducted toward finding replacements to some of the inorganic components of electro-devices suggest that the use of biodegradable components would be a better choice to conventional ones. Additionally, the unique features of such organic materials suggest they will be useful in biofunctional electronics; demonstrating functions that would be inaccessible for traditional inorganic compounds (Mihai *et al*, 2012). Such materials may lead to fully biodegradable and even biocompatible/biometabolizable at their E.o.L. for many low-cost applications. Experimental tests have shown that the integration of active organic materials into e-devices has allowed for the implementation of electronics with plastic substrates (Maria *et. al*, 2011; Seigel and Barlow, 2014), and thus low-cost, lightweight, and flexible sensing devices. Such usage is currently been proposed in the field of environmental monitoring, military defence and preventative medical care. Advancements in biomaterial processing and organic electronic device fabrication have allowed for the potential integration of biomolecules as active components in all of the materials employed in the realization of an organic transistor including the bulk substrate, the dielectric interface, (Schwabegger *et al*, 2011; Mihai *et al*, 2012; Mihai *et al*, 2013) and even the active semiconducting layers and electrodes.

According to the research by Schwabegger *et al*., the assembly of metal-oxide and organic passivation layer combines the properties of the high diunelectric constant of the metal oxide and the good organic–organic interface between semiconductor and insulator provided by a thin capping layer on top of the AlOx film (Schwabegger *et al*, 2011). The findings shows that the organic field effect transistors operates with lower voltages, while exhibiting field effect mobilities exceeding 3 $cm^2 V^{-1} s^{-1}$. With this findings they suggested that it is possible to produce high mobility, low voltage operating C_{60} based n-type organic field effect transistors for EEE. Also, electronic circuits on paper have been the subject of a recent extensive review. Paper substrates have been used for flexible electrowetting displays, as well as thermochromic displays for disposable consumer products. Low-voltage active circuits have been realized on banknotes, for anti-counterfeiting applications. It was shown that despite the surface roughness of banknote paper (Mihai *et al*, 2012), OFETs operating at less than 1 V with mobilities of 0.2 cm^2/Vs could be fabricated reliably. Encouraging performance has been demonstrated for paper-based organic photovoltaics.

Another reports by Mihai *et al*. (2012) on “Green and biodegradable Electronics” suggested that Silicon-based electronics can also be fabricated onto silk, and the silk can be used as a bioresorbable carrier to introduce the electronic element in vivo. Where silk can function as an effective solution-processed gate insulator for OFETs (Maria *et. al*, 2011; Mihai *et al*, 2012; Mihai *et al*, 2013), supporting very high mobilities of ~23 cm^2/Vs in pentacene combined with low-voltage operation. That silk has been used as a substrate for passive rf-ID circuits that can be integrated directly onto food, i.e., apples, eggs, etc., as sensors of food quality. In additional, silk can be fully biodegradable and could be engineered to degrade under chosen conditions, allowing selected drug storage and delivery.

These findings also identify protein-based material is gelatin, (Mihai *et al*, 2012) used commonly for capsules for oral drug ingestion as a good substance for e-components. It was also found to be fully biocompatible and biodegradable. Many electronics built on hard gelatin could easily be ingested for specific biomedical applications targeting short examination time. The production of organic field effect transistors components directly onto hard gelatin capsules has been demonstrated (Maria *et al*, 2011). Accordingly, Maria *et al,* 2011, findings also showed that the protein albumin, from chicken egg whites, has been publicised as a high performance cross-linkable solution processed material for organic field effect transistors dielectric. Protein-based materials for sustainable applications have been recently reviewed.

In addition to electronic conduction, several materials with a bio-origin are ionic conductors (Mihai *et al*, 2012). Earliest organic electronic ‘device’, a resistive switching element, was designed based on melanin, a biological polymeric material responsible for brown-black pigmentations found in animals, including humans (Maria *et al*., 2011). Since the first reports on conductivity in melanin, it has been employed in several sandwich diode type devices. Proton-conducting materials, extensively researched for fuel cell applications, have recently been documented as huge prospect in biocompatible electronics. Many conducting polymers are uniquely suited as bioelectronics interface materials because they can conduct both ionic and electronic currents. Both modes of conduction have potential application in biodegradable electronic products as well as biomedical devices. These common conducting polymers have been shown to be nontoxic and remarkably biocompatible (Schwabegger *et al*, 2011; Maria *et al*., 2011).

Table 2: Biodegradable as Replacement for Inorganic Components in EEE Production

Emerging Component	Acronym	Likely Replacement	Application	Remark
High mobility, low voltage operating C60 based n-type Organic Field Effect Transistors NATURE: Organic IMPACT: Biodegradable at E.o.L	OFETs	Amorphous silicon based devices NATURE: Inorganic Component IMPACT: Hazardous at E.o.L	C60 based n-type transistors in radio frequency identification tags or light emitting devices Small scale commercial production in e-books fabricated photovoltaics	Biocompatible/Biodegradable: Fabrication of OFET devices directly onto hard gelatin capsules (ingested for specific biomedical applications) has been demonstrated (Maria *et al*, 2011).
Organic Light Emitting Diode NATURE: Organic IMPACT: Biodegradable at E.o.L	OLEDs	Glassware/ceramics chiefly employed in production of transistors, valves, diodes and LED components NATURE: Inorganic Component; Full degradation occurring after 500 to 1000 years IMPACT: Hazardous at E.o.L	Production of battery powered OLED used in battery-powered red/green light-emitting diode (LED) wingtips for a paper airplane circuit. OLEDs already making a large footprint in the market of flat panel displays	Biocompatible/Biodegradable: Such usage is currently been proposed in the field of environmental monitoring, military defence and preventative medical care (Maria *et. al*, 2011)
Organic Thin-film Transistors NATURE: Organic IMPACT: Biodegradable	OTFTs	Glassware/ceramics are chiefly employed in production of transistors, valves, diodes and LED components	Three-terminal electronic devices consisting of a thin organic semiconducting layer, an	Biocompatible/Biodegradable:

Emerging Component	Acronym	Likely Replacement	Application	Remark
at E.o.L		NATURE: Inorganic Component; Full degradation occurring after 500 to 1000 years IMPACT: Hazardous at E.o.L	insulating (dielectric) layer, and three conductive terminals, the source, drain, and gate.	
Organic Photovoltaics NATURE: Organic IMPACT: Biodegradable at E.o.L	OPVs	Conventional Photovoltaics	Small scale commercial production in roll-to-roll fabricated photovoltaics	Biocompatible/Biodegradable: Also, paper-based photovoltaics features a thin semi-transparent paper as a substrate, with a conducting polymer transparent electrode, organic active layer, and reflective back electrode all fabricated via low-temperature chemical vapour deposition

The summary of these research findings shows that natural substrates and dielectrics offers an affluence of natural materials choice that could be integrated into various organic electronic devices, offering alternatives for biocompatible, biodegradable, and even bioimplantable and bioresorbable applications (Table 2). On the other hand, investigations into biocompatible semiconductors remain sparse (Mihai *et al*, 2012). Therefore, organic materials are uniquely suited to produce electronics that cannot only be sustainable and biodegradable, but can also have functionalities inaccessible to standard crystalline semiconductors, such as the functionalities required in many biomedical applications.

POLICY DIRECTION TOWARD BIODEGRADABLES ELECTRO-COMPONENTS

The intense trade of used EEE and better access to lower priced ICT equipment, especially in the developing counties, requires the application of Environmental Sound Management (ESM) of e-waste.

In the field of waste management, EPR is a strategy designed to promote the integration of environmental costs associated with EEE throughout their life cycles into the market price of the products. EPR is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact of EEE, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal.

The Basel Convention Partnership Programme, particularly within the Mobile Phone Partnership Initiative (MPPI) and the Partnership for Action on Computing Equipment (PACE) has been working toward addressing the issue of differentiating between used EEE as a second-hand good and e-waste. Manufacturers are now advised to enclose leaflets information on e-waste management and champion best strategy to involving business and industry in "Corporate Citizenship Responsibility" programmes, including the Extended Producer Responsibility and the Buy-back mechanism (Basel Convention, 2011a). In Nigeria, the introduction of a Buy-Back mechanism is yet to gain ground because of government haziness in enforcing a sound EPR programme on e-waste (NESREA, 2011). However, a mobile phone manufacturer, NOKIA has embarked on the collection of used mobile phone in 83 buy-back centres in Nigeria (Osibanjo, 2009). Samsung, another EEE manufacturing firm, produced 45 million OLED displays in 2011 and projects to build up to 600 million units by 2015 (Mihai et al, 2012), whereas printed flexible photovoltaics are currently commercialized at a smaller scale for rooftop and small appliance applications.

This review has identified and suggested the compatibility of biomaterials and e-devices in the manufacturing of EEE. Best applicable ESM include systems and technologies that yield multiple gains in the field of environmental protection, working conditions and employment creation, as well as in general economic terms. Such practices encourages the formal application of the WEEE 5Rs (Reduce, Repair, Reuse, Recycle and Recover) (NESREA, 2011), minimize occupational and environmental hazards as well as promote economic benefits. Therefore, the use of biodegradable materials in the manufacturing of EEE would at the long run retain substances that are eco-friendly at their end-of-life and save scenic resources.

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