DEVELOPMENT OF VALUE-ADDED MATERIALS FROM MUNICIPAL PLASTIC SOLID WASTE

by

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June 2020

DECLARATION

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DEDICATION

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ABSTRACT

Continuous consumption of plastic materials that brings about rapid and more plastic wastes (PWs) generation has become an issue of concern globally, specifically in low-income countries (LCs) where waste management services are still at an infant stage and are inadequate and unstainable. The explosion and acute generation of PWs are dependent on many factors including, incessant migration of citizens in search of greener pastures from rural areas to cities and continuous influx of economic migrants from surrounding African nations and other nations of the world to sub-Sahara Africa (SSA) region, changes in consumption pattern, rapid economic and industrial growth etc. The most startling thing about the severe plastic waste (PW) generation is that many citizens are not even aware of the negative/damaging impact of their activities on public health and the natural environment. Besides, the management of PW is now a challenge owing to factors like; insufficient budget for waste management (WM), unavailability of land spaces in cities for the construction of new disposal facilities, bad legislation and policies; and poor education and awareness campaigns. Hence, this study aims to enlighten the populace on the need for a change of attitude and behaviour towards municipal plastic solid waste management and to support recycling for greener cities and a sustainable future. To achieve this, a cross section of the students of the University of Johannesburg, South Africa were interviewed via a structured questionnaire survey and a logistic prediction model was developed to evaluate the attitudes and behaviours of the students towards recycling. Moreover, polystyrene plastic wastes (PSPWs) were recycled via solvothermal technique (chemical recycling) where a hybrid organic-inorganic nanocomposite (a value-added material) was developed. The synthesised nanocomposites (NCs) were characterized by XPS and EDX; XRD, FTIR, SEM, TEM and DLS; TGA, DSC and BET. Moreover, the neat (control) and unprocessed recycled polystyrene (rPS) were also characterized by NMR and GPC.

Furthermore, mechanical properties of the developed hybrid NCs were tested via nanoindentation techniques (which includes, nanohardness, elastic modulus, elastic strain recovery and anti-wear resistance). Based on the results of the analysis from the logistic model prediction, it was found that the majority of the respondents were not properly enlightened on waste matters and recycling activities. Similarly, the results from the developed hybrid NCs showed improvement in thermal and mechanical properties of the synthesized nanocomposites due to the inclusion of nanoparticles into the polymer matrix. The XRD revealed that recycled polystyrene (rPS)/recycled expanded polystyrene (rEPS) were crystallized after the addition of metallic precursors. XPS and FTIR results showed successful incorporation of metallic elements in the polymer matrix. It was concluded that polystyrene plastic wastes can be better recycled via the incorporation of metallic precursors into polymer matrix.

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LIST OF ACRONYMS

BPA	Bisphenol A
C & D	Construction and Demolition
C2C	Cradle to Cradle
C2G	Cradle to Grave
CE	Circular Economy
CIS	Commonwealth of Independent States
EC	European Commission.
EIs	Economic Instruments
EP	Epoxide
EPR	Extended Producer Responsibility
EU	European Union
GHGs	Greenhouse Gases
HCs	High-income countries
HDPE	High-Density Polyethylene
ICI	Industrial, Commercial and Institutional
KS	Kerbside Collection
LCA	Life Cycle Assessment

LCs	Low-income countries
LDPE	Low-Density Polyethylene
LSs	Landfill Sites
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NAFTA	North American Free Trade Agreement
NGOs	Non-Governmental Organizations
NRF	National Research Foundation
PAYT	Pay As You Throw
PET	Polyethylene Terephthalate
Pops	Persistent Organic Pollutants
PP	Polypropylene
PPP	Polluter Pay Principle
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl Chloride
PW	Plastic Waste
rEPS	recycled expanded Polystyrene
rPS	recycled Polystyrene

SDGs	Sustainable Development Goals
SMEs	Small and Medium Scale Enterprises
SSA	Sub-Saharan Africa
SSWM	Sustainable Solid Waste Management
SW	Solid Waste
UN	United Nation
UP	Unsaturated Polyester
WM	Waste Management
ZW	Zero Waste

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CHAPTER ONE

1.0 Introduction

1.1 Background

Globalization, rapid population growth, industrialization and changes in consumption pattern have been recognized as some of the major causative factors to the acute generation of municipal solid waste (MSW) across the world [1-5]. Due to the growing rate of MSW, waste management (WM) sectors are currently experiencing complexity in managing MSW and plastic waste (PW) specifically [6]. The management of PW is currently an issue of huge concern to stakeholders and the general public [7]. In sub-Saharan Africa (SSA), the challenges of PW and MSW management are poor government funding, poor legislation and policies, and poor awareness campaigns [8]. As cities' population rises and the amount of MSW generation grows; health of public and the environment are being threatened by this continuous increase and by the improper methods of disposal [9-13]. Improper disposal occurs especially when PW/MSW remains uncollected which may be due to low service coverage in many cities in developing countries (DCs) [14]. The uncollected MSW typically serves as a propagating ground for pests and thereby spreading diseases to the masses [15]. The bulk of the waste being generated is largely PW which its present methods of management are unsustainable [16]. Poor disposal of PW places damaging effects on the populace and the ecosystem [17]. In SSA, the most popular methods for PW management are incineration and landfilling [16]. While incineration releases poisonous elements to the atmosphere [18], landfilling is not the best option as PW deposited to landfills causes harms. When PW is landfilled, it does not degrade instantly but occupies the landfills for a period of about one thousand year and in the end it breaks down, leaching toxic materials into the soil thus polluting surface and underground water, and surface and underground soil and resulting in water and soil pollution [19, 20]. Besides, landfilling is becoming obsolete in many continents of the world including Africa on account of unavailability of land spaces for the construction of new landfill facilities in urban areas [18, 19, 21].

Many nations of the world including South Africa are currently faced with the challenges emanating from the increased volumes of PW generation and these issues may continue if the current method of WM which is purely disposal of PW to landfills continues [22]. The alternative method that can be used by developing nations to curb this menace is to introduce a sustainable solid waste management (SSWM) program through a recycling scheme. This program will assist in addressing PW explosion issue. The starting point for the success of any recycling program is awareness creation/campaign to the public. The recycling program will help to bring the public and all stakeholders together for proper involvement/participation. As part of the awareness campaign/public involvement, students of Institutions of Higher Learning (IHL) (such as, the Universities, Polytechnic, Colleges etc.) who are believed to be having some degree of influences over their family members because of their levels of exposure would be the best chosen samples at the commencement of the campaign [22]. Presently, level of awareness on PW recycling is very low and this is affecting the attitudes and behaviours of the masses towards supporting recycling [23]. Today, it has been shown that the majority of the problems associated with improper PW management including, environmental pollution and other health related issues are caused by the activities of members of public [23]. The most remarkable thing is that most of them do not know the magnitude of the damage being done/impact their activities are triggering on public health and the ecological environment and several municipalities in low-income countries (LCs) are not making enough efforts in the area of education/awareness campaign to encourage public participation on recycling [23]. Thus, urgent interventions are required to minimize the impact of PW and one of these interventions is in the creation of awareness campaign [24].

Furthermore, the challenges posed by PW to public health and the environment can also be addressed through the development of valuable materials (hybrid materials) with better design and enhanced properties from PW using chemical recycling method [25]. The hybrid materials are novel materials arising from the blending of organic polymer with inorganic metallic precursors and thereby producing materials with a better property for varied applications. Up till now, little or no study has evaluated the level awareness of public on waste recycling in a bid to prepare them for a recycling program, and then developed advanced materials from MSW in the same study and confirmed the enhancement of the thermal and mechanical properties of the developed composites for potential applications in water treatment.

In this study, the attitude and behaviour of the public with regards to MSW and PW management were evaluated as the primary way to reduce PW issues in the environment and thereafter novel hybrid organic-inorganic nanocomposites were developed from recycled polystyrene (rPS) and recycled expanded polystyrene (rEPS) via solvothermal technique and the properties of the hybrid materials were studied.

1.2 Problem Statement

Plastics production has been increasing exponentially from where it rose to around ~300 million metric tons between 2013 and 2014 respectively [26, 27]. Currently, on a global scale, the amount of plastic materials that are disposed of after initial application is about 95% of the total amounts produced and its economic worth has been estimated to nearby $100 billion yearly [28]. The more plastic materials are utilized by the populace, the more the growth of PW [29]. The fast rate of PW generation goes hand-in-hand with its impacts on the environment [30]. Most of the PWs generated ended up in the ocean and this has contributed largely to environmental issues and death of many thousands of marine animals [31]. PW is often blown away by wind into drainages and in the end it gets into the sea [32, 33], where marine animals swallow them because the animals frequently confused the plastic fragments for food and in many cases when the waste passes through their guts, it settled in their digestive tracts and leads to suffocation [34, 35]. Furthermore, the disposal of used plastic materials has become a source of concerns for the general populace due to its negative health implication on the public and negative impact on ecosystem [31]. Currently, PW generation and disposal is a prime concern for researchers and policy makers [31].

A recent study revealed that South Africa consumed about 8 billion plastic bags yearly. [33, 36]. The increase in the utilization of plastic bags is resulting in large quantity of waste plastics. PWs generated in South Africa are now growing at a symmetrical rate due to population explosion resulting from rural-urban migration and influx of economy migrant from surrounding nations [37]. Now, the rate of recycling output is very low. For example, in 2014, the total quantity of PWs generated in South Africa was about ~1.5 million tons, the amount recycled was less than ~0.5 million tons and the quantities that was deposited to the landfills were about ~1.2 million tons [38]. Apart from its daily increment, plastic waste is a menace, burden on the environment that needs to be managed sustainably but the methods of disposal as per incineration and landfilling are unsustainable since these methods pose negative impact on the environment. PW is now a serious challenge to many WM municipalities in the developing nations [39-41].

Furthermore, apart from primary recycling and secondary, the focus of PW recycling has also been on pyrolysis of plastic materials to manufacture oil which can be subsequently transformed to obtain fuels. Inappropriately, there is an issue of the optimal temperature of one plastic being too low for the decomposition of the other [42]. Also, since waste plastics are the feedstocks used in pyrolysis, additional analysis are required to obtain a product of better quality [43]. Owing to all these, researchers have been studying different materials as a means of addressing PW issue [42]. Recently, researchers have started investigating into hybrid materials that can be used for diverse applications [44]. Hybrid materials refer to the blending of two or more substances to obtain a better property that cannot be found in a singular material when it is alone used. Many of these hybrid materials display unique properties after the impregnation of different materials and in the end, novel functionalities are produced [45, 46]. Despite this, compatibility or miscibility, degradability and chemistry of most materials are having huge challenges since many do not blend together [47]. Similarly, high temperature is required in preparing many materials which is a bit challenging and, in some cases, affects the properties of the developed materials.

In this study, recycled polystyrene (rPS) and recycled expanded polystyrene were impregnated into metallic precursors to develop novel hybrid novel organic-inorganic nanocomposites (NCs) of better properties. Besides, the level of awareness of people were evaluated with respect to PW and MSW recycling in general.

1.3 Research Questions

1. What are the results of the incorporation of inorganic precursors into polymer matrix at different impregnation ratio?
2. What are the thermal and mechanical behaviour of the hybrid organic-inorganic nanocomposites developed from polystyrene wastes?
3. What are the levels of awareness of people with regards to plastic waste management/municipal solid waste management in general?
4. What are the characteristics/features of the synthesized hybrid organic-inorganic nanocomposites?

1.4 Purpose and aims of the research

The primary aim of this study is to develop hybrid nanocomposites from recycled polystyrene. The specific objectives are as follows;

1. To assess the attitude and behaviour of people with respect to plastic waste recycling.
2. To recycle polystyrene waste via chemical recycling method (solvothermal technique).
3. To study the development of nanocomposites from polystyrene wastes and the influence of incorporating nanoparticles into polymer matrix in determining the thermal stability and mechanical strength of the hybrid organic-inorganic nanocomposites.
4. To study the compositional, morphological and structural properties of nanocomposites in order to determine its potentials for deployment into water treatment (photocatalysis).

1.5 Hypothesis

The hypothesis in this study are as follows;

1. We hypothesize that knowledge of students and staff with respect to waste management and recycling would be inadequate.
2. We hypothesize that value-added materials (hybrid nanocomposites) for applications in water treatment (photocalysis) would be developed from recycled polystyrene.
3. We hypothesize that iimpregnation or functionalization of inorganic metallic compounds and organic polymers would generate materials with advanced applications.
4. We hypothesize that thermal and mechanical properties of hybrid nanocomposites from recycled polystyrene would be enhanced.
5. We hypothesize that developing hybrid nanocomposites from recycled polystyrene waste which will assist in addressing the dire *issues of environmental,* economic and health associated with the poor management of plastic wastes.

1.6 Scope of the Work

The scope of this work comprises of the impregnation of organic polymer (plastic waste) alongside metallic precursors (inorganic materials) for the development of nanocomposites (NCs) from recycled polystyrene (rP) (lunch box) and recycled expanded polystyrene (rEPS) (packaging materials). The organic polymers were dissolved in organic solvents (xylene and chloroform) and the inorganic precursors were blended together at different impregnation ratios. Samples were prepared via solvothermal method at a temperature of 250 ℃ for 3 hr. Afterwards, dried solid powdered NCs were obtained and analysed. Comprehensive characterization of the synthesized materials was conducted. The compositional and structural characterization via XPS and EDS; XRD and FTIR were carried out. The morphological studies were carried out by SEM, TEM with SAED pattern and the particle size diameters by DLS. Analysis of the thermal stability and phase changes were done via TGA and DSC respectively. Moreover, surface area analysis, chemical shift and molecular weight distribution were evaluated by means of BET, NMR and GPC. Finally, nanoindentation technique was employed to study the mechanical properties (such as hardness, elastic modulus, elastic strain recovery and anti-wear resistance) of the NCs.

1.7 Justification to the Study

Development of value-added materials (nanocomposites) from recycled plastic materials is an uncharted terrain in sub-Sahara Africa Continent especially in solid waste (SW) recycling process. Although some studies have been conducted globally but not exactly on recycled polymer. This study will assist to discover the beneficial utilization of waste plastics for several applications including deployment of nanocomposites for wastewater treatment. It will also serve as a means of curbing environmental menace that relates to its disposal to landfills. It will also provide a platform to study the potential of waste plastic as a cost-effective material. South Africa is presently faced with issues of PW that results from domestic and industrial activities of the citizens. The impact of this waste is so enormous, and it includes pollution of water, land, air and the overall environment. One of the resultant effects of PWs proliferation on the environment is flooding. This PW can be recycled, and resource can be recouped from it and can serve as raw material for other applications in the recycling industries. Thus, any study aiming at improving the property of polymer wastes through the utilization of waste plastic for a potential application can be regarded as a good initiative in combating climate change.

1.8 Structure of the Thesis

Chapter 1 of this thesis reports a general background information on MSW management and challenges associated with rapid generation of PW, motivation for developing value-added materials from recycled polystyrene, purpose and aim of this research, hypothesis, justification for the study and scope of this research. A total of four (4) articles and a chapter in a book were compiled from the results of the findings where some have been published, accepted for publications and others are currently under review in peer-reviewed and reputable ISI journals. **Paper 1** and **Paper 2** are reported in Chapter Two. **Paper 1** reviewed the challenges of PW generation and management in sub-Saharan Africa (SSA). The study provided an overview of plastic lifecycle and difficulties related with its management; these include, current practices, public opinion, and government regulations. The study also highlights the impact of plastic waste proliferation on man and the global environment; the economic and environmental benefits of proper plastic waste management. Significant analysis of current processes and the appropriateness of potential solutions were provided as the basis for proposition on mitigation measures to avert the negative impact of plastic waste on public health and the natural environment. One of the potential solutions discussed was the chemical recycling method (tertiary recycling) which is a promising method and an improvement measure to mitigate the proliferation of plastic wastes (PWs). This novel technique was discussed in **Paper 2**. The method was employed for the development of value-added hybrid organic-inorganic nanocomposites. The section further outlined polystyrene materials and PWs, organic-inorganic hybrid materials from PWs, solvothermal and hydrothermal methods. Chapter Three presented the published, accepted and submitted papers currently under review. All these papers are connecting to one another and they are arranged in chronological order of importance to achieve the set objectives of the study and they also offered answers to the research questions in this study. **Paper 3** studied the perception, attitudes and behaviour of the public regarding waste management and recycling. The students of the University of Johannesburg were chosen as samples. The waste education exercise was carried out using a structured questionnaire to enlighten the students on the need to participate in a sustainable solid waste management (SSWM) (recycling process). The paper analysed and discussed the results obtained from the structured questionnaire via a logistic model prediction. The statistical analysis of the data produced evidence of relationships between the data, and in addition, the variables obtained from the survey and the analysis allowed for the development of a logistic model prediction for the assessment of attitudes and behaviour of the students towards a sustainable solid waste management. **Paper 4 and Paper 5** delved into the chemical recycling of PWs where value-added materials (novel hybrid organic-inorganic NCs) were developed from the waste polymers. The materials developed were characterized by various analytical techniques including, X-ray photoelectron spectroscopy (XPS) for elemental compositions, X-ray diffraction (XRD) for crystallinity, Fourier transform-infrared (FTIR) for interface affinity, Scanning electron microscopy (SEM), Transmission electron microscopy (TEM) and Dynamic Light Scattering (DLS) for morphology, homogenous dispersion of nanoparticles within the rPS matrix and particle size diameter. Moreover, the Thermogravimetric analysis (TGA) for the enhancement of thermal stability, Differential scanning calorimetry (DSC) for evaluation of glass transition temperatures, Brunauer-Emmett-Teller (BET) for the determination of surface area, pore volume and pore size, Nuclear magnetic resonance (NMR) for the evaluation of chemical shift in polymers and Gel permeation chromatography (GPC) for the determination of molecular weight (Mw) distribution of polymers dispersed in an organic solvent and nanoindentation studies for the evaluation of the mechanical properties of the organic-inorganic nanocomposites (NCs). The papers that resulted from this work are as follows;

Paper 1: **Ayeleru O. O.,** Dlova, S., Ntuli, F., Kupolati, W. K, Marina P. F., Blencowe, A., Olubambi, P. A. (2019). Challenges of plastic waste generation and management in sub-Saharan Africa: A review (**Published in Waste Management**).

Paper 2: **Ayeleru, O. O.,** Dlova, S., Akinribide, O. J., Olorundare, O. F., Ntuli, F., Kupolati, W. K., Olubambi, P. A. (2020). Potential innovative technique for the management of polystyrene waste in South Africa (**Accepted in CRC, Taylor & Francis**).

Paper 3: **Ayeleru O. O.,** Gbashi S., Akinribide O. J., Ramatsa I., Ntuli, F., Kupolati, W. K., Nick Fewster-Young, Olubambi, P. A. (2019). Recycling attitudes and students' behaviours towards municipal solid waste management at the University of Johannesburg, South Africa (**Under review in The Journal of Solid Waste Technology and Management**).

Paper 4: **Ayeleru O. O.,** Ntuli, F., Kupolati, W. K, Marina P. F., Blencowe, A., Olubambi, P. A. (2019). Novel green route towards synthesis of recycled polystyrene-based nanocomposites via solvothermal technique (**Under review in Pollution Research**).

Paper 5: **Ayeleru O. O.,** Akinribide O. J., Olorundare O. F., Kempaiah D. M., Hall C., Ntuli, F., Kupolati, W. K., Olubambi, P. A. (2019). Nanoindentation studies and characterization of hybrid nanocomposites based on solvothermal process (**Published in Inorganic Chemistry Communications**).

The Chapter Four of this thesis gives the summaries and the connections between all the papers developed in this study. It also provides arguments for the novelty and contribution of the present study to the existing knowledge in the organic-inorganic nanocomposites. Inferences were drawn from the findings and recommendations were made for future works. Moreover, all the papers in this thesis were placed as it appears in each journal without making any changes to them. Hence, the referencing styles may differs based on journal requirements.

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Challenges of plastic waste generation and management in sub-Saharan Africa: A review

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ABSTRACT

Recently, the issues of land-based plastics and their associated challenges in the marine world have been widely publicised in the media and scientific literature. Thus far, despite these communications, there have been few reports that have focused on the issues that acute plastic waste generation and its poor management pose to human health and the global environment. Also, articles on ways to mitigate these issues particularly in sub-Saharan Africa have not been documented. Indeed, there is significant scope for improvements in plastic waste management in developing countries, which offer a wide range of economic and environmental benefits. Plastic waste generation in sub-Saharan Africa is dependent on many factors like urbanization, etc. Currently, the population of sub-Saharan Africa is around 1 billion as of the year 2019, the amount of generated waste is 180 million tonnes at the rate of 0.5% per capita per day, the amount that is openly dumped is 70% and the plastic waste generated annually is 17 million tonnes. Therefore, this study aims to provide an overview of the plastic lifecycle and problems associated with plastic waste management in sub-Saharan Africa, including current practices, public participation and opinion, and government regulations. In addition, this highlight aims to outline the impact of plastic waste proliferation on man and the environment; and the economic and environmental benefits of proper plastic waste management. Critical discussion of current processes and the suitability of potential solutions provide the basis for proposition on mitigation measures to avert the negative impact of plastic waste.

Contents

Abbreviations: SW, Solid Waste; MSW, Municipal Solid Waste; MSWM, Municipal Solid Waste Management; MPSWM, Municipal Plastic Solid Waste Management; WM, Waste Management; SSWM, Sustainable Solid Waste Management; SD, Sustainable Development; PW, Plastic Waste; CIS, Commonwealth of Independent States; NAFTA, North American Free Trade Agreement; GHGs, Greenhouse Gases; SSA, Sub-Saharan Africa; SDGs, Sustainable Development Goals; Pops, Persistent Organic Pollutants; BPA, Bisphenol A; NGOs, Non-Governmental Organizations; CE, Circular Economy; C2C, Cradle to Cradle; LCA, Life Cycle Assessment; C2G, Cradle to Grave; NRF, National Research Foundation; ACTB, Applied Chemistry and Translational Biomaterials; CO_2, Carbon Dioxide; CH_4, Methane; N_2O, Dinitrogen Monoxide; UN, United Nation; C & D, Construction and Demolition; ICI, Industrial, Commercial and Institutional; FW, Food Waste; GW, Green Waste; PET, Polyethylene Terephthalate; HDPE, High-Density Polyethylene; PVC, Polyvinyl Chloride; LDPE, Low-Density Polyethylene; PP, Polypropylene; PS, Polystyrene; UP, Unsaturated Polyester; PU, Polyurethane; EP, Epoxide; PAYT, Pay As You Throw; PPP, Polluter Pay Principle; EPR, Extended Producer Responsibility; ZW, Zero Waste; EU, European Union; KS, Kerbside Collection; LSs, Landfill Sites; SMEs, Small and Medium Scale Enterprises; LCs, Low-income countries; HCs, High-income countries; EIs, Economic Instruments; EC, European Commission; PSWs, Polystyrene Wastes; MR, Mechanical recycling; CR, Chemical recycling; PMs, Plastic materials

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CHAPTER TWO

Paper 1: **Challenges of plastic waste generation and management in sub-Saharan Africa: A review**

(Published in Waste Management)

Abstract

Recently, the issues of land-based plastics and their associated challenges in the marine world have been widely publicised in the media and scientific literature. Thus far, despite these communications, there have been few reports that have focused on the issues that acute plastic waste generation and its poor management pose to human health and the global environment. Also, articles on ways to mitigate these issues particularly in sub-Saharan Africa have not been documented. Indeed, there is significant scope for improvements in plastic waste management in developing countries, which offer a wide range of economic and environmental benefits. Plastic waste generation in sub-Saharan Africa is dependent on many factors like urbanization etc. Currently, the population of sub-Saharan Africa is around 1 billion as of the year 2019, the amount of generated waste is 180 million tonnes at the rate of 0.5% per capita per day, the amount that is openly dumped is 70% and the plastic waste generated annually is 17 million tonnes. Therefore, this study aims to provide an overview of the plastic lifecycle and problems associated with plastic waste management in sub-Saharan Africa, including current practices, public participation and opinion, and government regulations. In addition, this highlight aims to outline the impact of plastic waste proliferation on man and the environment; and the economic and environmental benefits of proper plastic waste management. Critical discussion of current processes and the suitability of potential solutions provide the basis for proposition on mitigation measures to avert the negative impact of plastic waste.

Keyword: Circular economy, economic benefits, environmental benefits, health risk, plastic waste management, recycling

Abbreviations: SW, Solid Waste; MSW, Municipal Solid Waste; MSWM, Municipal Solid Waste Management; MPSWM, Municipal Plastic Solid Waste Management; WM, Waste Management; SSWM, Sustainable Solid Waste Management; SD, Sustainable Development; PW, Plastic Waste;

CIS, Commonwealth of Independent States, NAFTA, North American Free Trade Agreement; GHGs, Greenhouse Gases; SSA, Sub-Saharan Africa; SDGs, Sustainable Development Goals; Pops, Persistent Organic Pollutants; BPA, Bisphenol A; NGOs, Non-Governmental Organizations; CE, Circular Economy; C2C, Cradle to Cradle; LCA, Life Cycle Assessment; C2G, Cradle to Grave; NRF, National Research Foundation; ACTB, Applied Chemistry and Translational Biomaterials; CO_2, Carbon Dioxide; CH_4, Methane; N_2O, Dinitrogen Monoxide; UN, United Nation; C & D, Construction and Demolition; ICI, Industrial, Commercial and Institutional; FW, Food Waste; GW, Green Waste; PET, Polyethylene Terephthalate; HDPE, High-Density Polyethylene; PVC, Polyvinyl Chloride; LDPE, Low-Density Polyethylene; PP, Polypropylene; PS, Polystyrene; UP, Unsaturated Polyester; PU, Polyurethane; EP, Epoxide; SDGs, Sustainable Development Goals; PAYT, Pay As You Throw; PPP, Polluter Pay Principle; EPR, Extended Producer Responsibility; ZW, Zero Waste; EU, European Union; KS, Kerbside Collection; LSs, Landfill Sites; SMEs, Small and Medium Scale Enterprises; LCs, Low-income countries; HCs, High-income countries; EIs, Economic Instruments; EC, European Commission; PSWs, Polystyrene Wastes; MR, Mechanical recycling; CR, Chemical recycling; PMs, Plastic materials

1. Introduction

In line with the United Nations (UN) report on municipal solid waste (MSW) generation, around 99% of goods originally bought for use by consumers are turned to waste after the first six months of acquirement and this has been one of the major factors that is escalating the amount of solid waste (SW) generated across the globe yearly (Wahlén, 2018). Incidentally, the bulk of this MSW happens to be plastic waste (PW) from which the majority are non-biodegradable and about ~300 million tonnes are being generated universally year after year (Tulashie et al., 2020). It is so regrettable that between 1950 and 2018, around 6 billion tonnes of PW were generated, the amount recycled was less than 10% and the quantity incinerated was equally less than 15% (The Economist, 2018). The implication of this is that close to 80% of PW is being sent to the landfills while there is currently a shortage of land for the construction of landfill facilities in many cities in low-income countries (LCs) (Ayeleru et al., 2016). Thus, PW has continued to litter the environment and block drainages whenever it is blown away by winds from the disposal sites (Jambeck et al., 2018). Moreover, some of the generated PW remain uncollected due to lack of regular waste management (WM) services or poor collection services that are so conventional in developing countries (DCs) (Ferronato & Torretta, 2019).

Although, some studies have attempted to address this issue of rapid proliferation of PW, little has been investigated leaving wide margins for improvement. Hence, there is paucity of information on PW generation and management in sub-Saharan Africa (SSA). Therefore, any paper that addresses plastic waste generation, its various methods of management and possible sustainable methods to manage PW and the risks associated with rapid PW generation is noteworthy. In this present paper, we made available a summary of the existing literature relating to the issues that plastic waste poses on public health and the ecological environment and the measures to forestall these issues in Africa and notably, in the SSA region. In this review, we gave keen interest to additives such as Bisphenol A (BPA) which brings about health impairment in humans. The major aspects of this paper gave the overview of this study and the research findings. The discussion section provided the summary of the study and highlighted the health issues connected with rapid plastic waste generation and the future research on plastic wastes.

2. Description of study area

SSA comprises of 48 nations and has the fastest rate of urban growth among regions globally (Saghir & Santoro, 2018) with the population of urban centres doubling between the year 2000 and 2015 (Urban Transformations, 2015). ACP-EU Joint Parliamentary Assembly reported that the population of urban areas was ~300 million in 2010 and projected to increase to 700 million by 2035 and it has likewise been forecast that by 2050, more than 50% of the global population would emanate from SSA (ACP-EC Joint Parliamentary Assembly, 2014; Kaza et al., 2018). OECD/FAO also stated that the total population of SSA currently represent 13% of the world population (> 1 billion) and is projected to rise by 22% (2.2 billion) by 2050 (Kaza et al., 2018; OECD/FAO, 2016). In the same vein, a recent study has shown that the amount of waste generated in SSA was about 180 million metric tonnes as of 2019 and the per capita generated waste was nearly 0.50 kg/capita/day (Kaza et al., 2018). Furthermore, some long-range forecasts have quoted that the global population could increase by 3.9 billion by the year 2100, and SSA will be occupying around 75% of the total world population (Bhorat et al., 2017). As the population of SSA rises, the region also faces some challenges, for example, threats on the veracity of the ecosystem and biodiversity but the rapid population growth also comes with benefits such as economic growth which creates extra demand for products and services and increase in workforce (Güneralp et al., 2017). Although, SSA nations are generally characterised by poor economic growth, some studies have attributed this as one of the key contributing factors to large scale waste production (African Development Bank, 2016; The Heritage Foundation, 2017). Moreover, a recent study has revealed that there is a correlation between poverty and waste generation, specifically, the organic waste since the unemployed do all their cooking of food which eventually results in large volume of organic waste (Ayeleru et al., 2018). For instance, in 2016, about 180 million tonnes of waste was generated at a rate of about 0.5% per capita per day with its bulk being food waste (FW) and green waste (Gwada et al.) (**Figure 1**), the amount of these wastes collected was less than 50% and the quantity that was openly dumped was around 70% (Kaza et al., 2018).

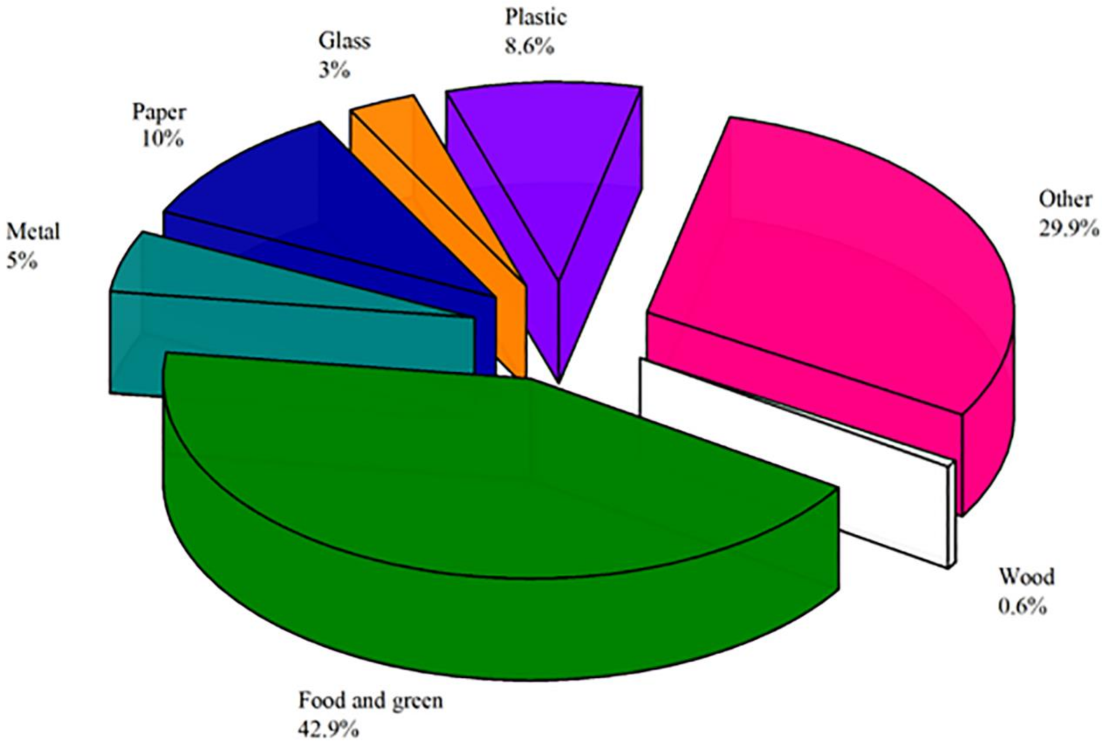

Figure 1: Municipal solid waste composition stream in sub-Saharan Africa

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With respect to WM, SSA is faced with a diverse range of challenges and these vary in terms of development across the region (Australian Government Department of Foreign Affairs and Trade, 2015, 2018). Some of the developmental issues include; a shortage of skilled WM experts and facilities, lack of a conducive environment for business and governance, and gender disparities which all contribute to poor PW and municipal solid waste management (MSWM) in general (Australian Government Department of Foreign Affairs and Trade, 2015, 2018). The poor economic growth in the region ultimately increases the level of poverty and is compounded by an increasing population, which adversely affect MSWM since the residents and their local governments are unable to afford WM strategies and this makes funding the services a bit difficult (Fengler & Devarajan, 2012). It has been shown that lack of clarity of functions among tiers or arms of government where the role of MSWM is not designated to local governments makes it a bit challenging for the residents to receive qualitative MSW services and these have resulted into improper PW management or irregular service coverage (Asea, 2018; Ganahl, 2013; Poncian & Mgaya, 2015; Yukalang et al., 2017). **Figure 2** shows waste collection coverage in SSA (Kaza et al., 2018).

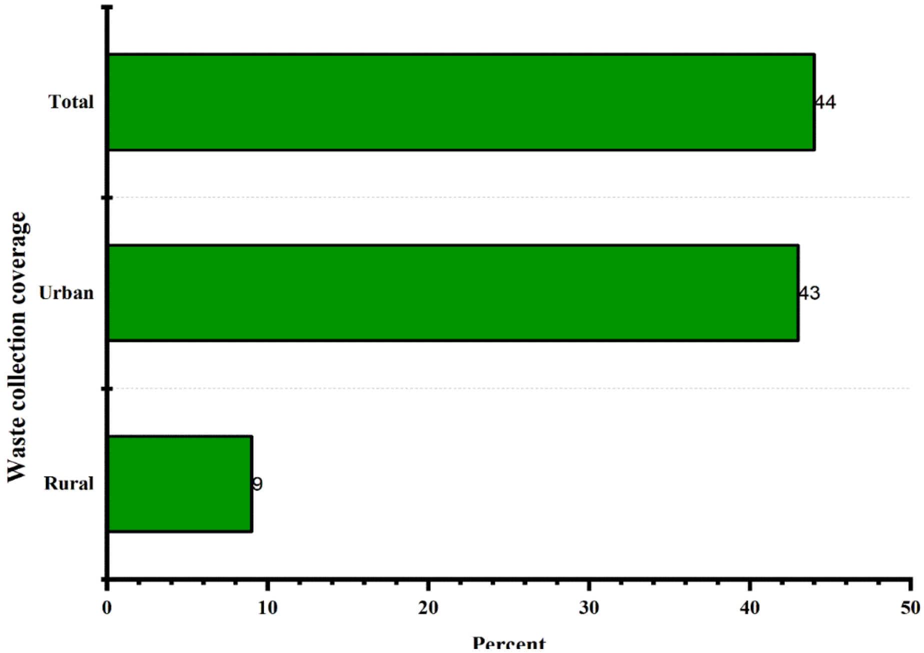

Figure 2: Coverage of waste collection in Sub-Saharan Africa

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In addition, India being the second leading populous nation globally, has a population of approximately 1 billion and the generated waste was around 60 million tonnes annually, the bulk of which is also organic waste (occupied almost a half of the total waste generated) like the SSA (Kamath, 2018; Kumar, 2017). It has also been established here that there is a connection between standard of living and waste generation since higher income earners generate more recyclables and inorganic waste while the low-income earners generate more organics (Kamath, 2018). As the cities expand, waste generation also increases but the attention of government is shifted towards provision of other amenities to cater for the rapid population while disregarding WM (Kumar, 2017; Swaminathan, 2018). WM faces a huge challenge in India especially with the pace of urbanisation in which about 380 million lives in the cities and it has been predicted that by 2030, around 600 million will be residing in urban areas. In spite of this, the amount of waste generated is more than double the population whereas methods of collection and disposal are very poor coupled with inadequate facilities leading to health and environmental issues (Chaturvedi & Kumar Gaurav, 2016).

3. Methods

In order to assess relevant information for this current review, several resource materials and databases such as; *Web of Science, ACS Publications, ScienceDirect, Access Engineering, Access Science, ProQuest Ebook Central, Cambridge Book Online, Cambridge Journal, Google scholar, Springer Link, Web Page, Policy documents, Government documents, Electronic books, Electronic articles* were all consulted. We were able to get pertinent information through all the platforms listed above via the use of appropriate key words and phrases (such as; "plastic waste recycling", "challenges associated with plastic waste", "health issues connected to plastic waste", “recycled plastic”, “economic benefits of plastic recycling”, “environmental benefits of plastic recycling”) during the search for the information. Any article in the course of the search was regarded as a related document provided it comes with the phrase “plastic waste” or “recycled plastic” while other parts of the titles were not included. Most importantly, challenges associated with plastic waste in SSA, benefits of proper plastic waste management, health-related issues to PW and mitigation measures were thoroughly explored. The relevant documents considered in this study were from 2008 to 2019 (a decade). At the end of the analysis, a total of over 200 articles were reviewed in the result section of this work where only 160 published articles were subjected to analysis without considering other documents and citations. By evaluating 160 published articles globally, this study presents a precis of the current information to policy makers, academics, government and non-governmental organisations globally.

4. Results

With regards to the relevant literature found, this review is structured into seven segments: Plastic production (Section 4.1), Current practices with respect to plastic waste management (Section 4.2), Drivers of plastic waste generation in the sub-Saharan Africa (Section 4.3), Authors’ opinion and recommendation on plastic waste reduction and novelty of the study (Section 4.4), Health risks and issues associated with acute generation of plastic waste (Section 4.5), Government policies, public participation and opinion; and solutions to plastic waste issues (Section 4.6), Benefits of plastic waste management/recycling (Section 4.7), Limitations of recycling (Section 4.8) and Discussion.

4.1. Plastic production

4.1.1. Global plastic and plastic waste production

Over the last 20 years, the global production of plastics has doubled to ~335 million tonnes (Hermabessiere et al., 2017; Oliveira et al., 2013; Open Government Licence, 2015; UNEP, 2018b; Wright et al., 2013; Wu et al., 2017) and is predicted to increase to ≥ 600 million tonnes by 2030 (UNEP, 2018b). Due to their versatile nature, plastic materials (PMs) are currently used in diverse applications and have become part of the lifestyles of people (Dhawan et al., 2019; Kumar et al., 2018). Between 2011 and 2015, the amount of PMs consumption has risen from about ~280 million tonnes to around ~320 million tonnes respectively (Aryan et al., 2019). The distribution of plastic production globally comprising, the Commonwealth of Independent States (CIS), North American Free Trade Agreement (NAFTA), Middle East and Africa; Latin America, Europe and Asia are stated as follows; Asia comprising of Japan, 3.9%; China, 29.4% and Rest of Asia, 16.8%. China occupies the largest at 29.4%, Europe at 18.5%, NAFTA at 17.7%, Middle East and Africa accounted for 7.1%, Latin America occupied 4% and CIS is the least producer of plastic which stood at 2.6% (PlasticsEurope, 2018 2019). More than 50% of the plastics produced globally are for single usage applications and become waste plastics following their initial applications. PMs can be grouped into two broad categories; the thermoplastics and the thermosets. The thermoplastics are usually linear or branched polymers that can be remoulded and are stable over a range of temperatures (Fagnani & Guimarães, 2017; OECD, 2018c). The thermosets are crossed-linked polymer which are usually rigid and irreversible (OECD, 2018c). The two broad classifications are further subdivided into seven classes which include; polyethylene terephthalate (PET) (Type 1); high-density polyethylene (HDPE) (Type 2); polyvinyl chloride (PVC) (Type 3); low-density polyethylene (LDPE) (Type 4); polypropylene (PP) (Type 5); polystyrene (PS) (Type

6); and others (Type 7) as produced by plastic industries (Hahladakis & Aljabri, 2019). These types of plastics pose a major challenge in WM (Hopewell et al., 2009), are responsible for causing soil and water pollution, and are a serious threat to terrestrial and aquatic ecosystems (UNEP, 2018a; Zelenika et al., 2018). As the population of urban centres increase and living standards improve, the amount of plastic waste (PW) generated also increases (Awasthi et al., 2017; Pankaj, 2015; Pickin & Randell, 2017; Singh & Sharma, 2016). In the last few years, the use of PMs has increased considerably in sub-Saharan Africa's capital territories, leading to a huge PW component of MSW (Quartey et al., 2015). The increasing generation of waste plastics in LCs is now a major source of concern to waste managers and policy makers since there are few corresponding facilities to manage these wastes (European Commission, 2011a). Whilst incineration and landfills are commonly used to dispose of PW, they are unsustainable and a serious burden on the environment (Moharir & Kumar, 2019; Nemade & Thorat, 2013; Oteng-Ababio et al., 2013; Rokade, 2012; UNEP/IETC, 2009). Furthermore, the poor disposal of PW, which includes illegitimate dumping and burning, is also a source of health and environmental implications (MiliosEsmailzadeh Davani et al., 2018). In the past, municipal governments in various nations of SSA have not had the necessary regulatory support or funding to mitigate issues associated with PW as it had not been classified as one of the major components in plans (Domingo, 2013). However, PW is now one of the main constituents of MSW streams (Çelikgöğüs & Karaduman, 2015; Gwada et al., 2019; Hadi

Figure 3 showed the distribution of PW generated globally from 1950 to 2015 (Geyer et al., 2017).

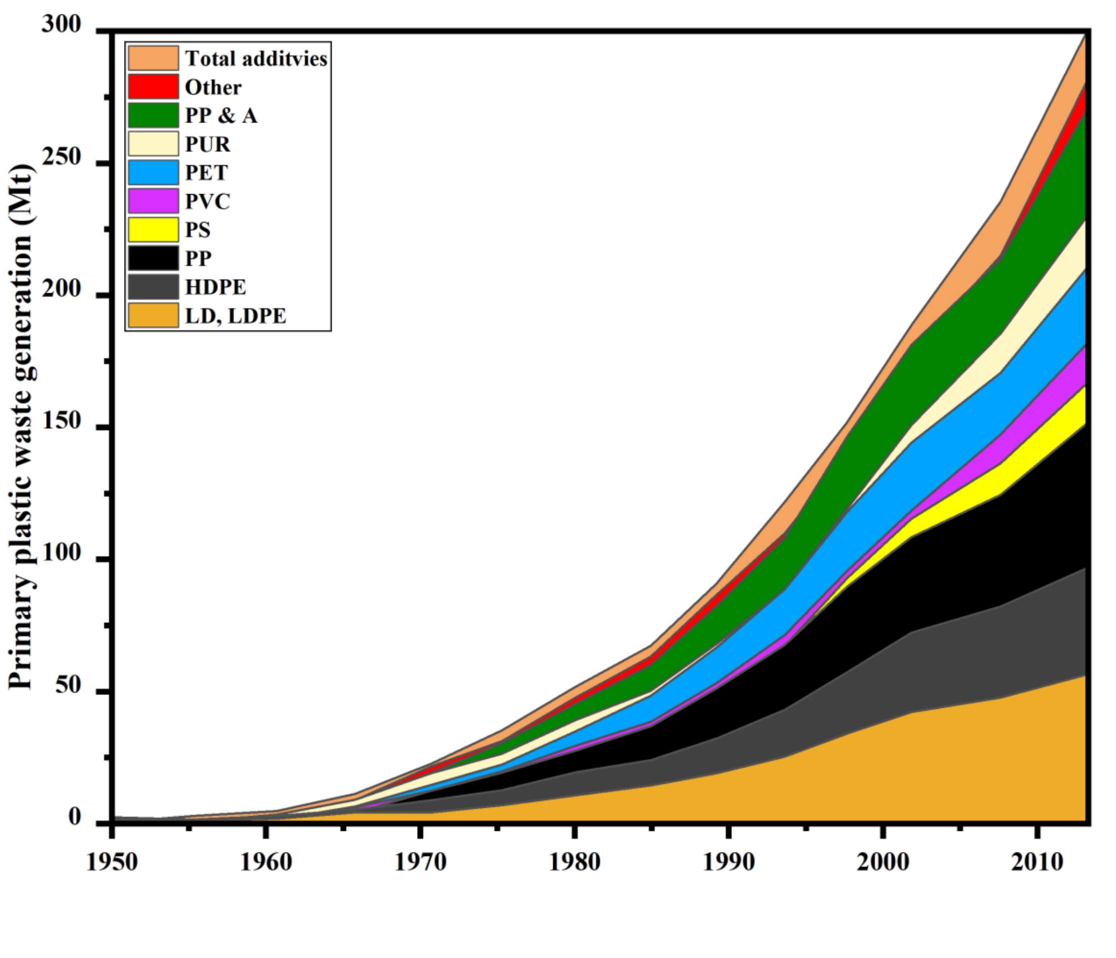

Figure 3: Distribution of plastic waste generated (in metric million tonnes) globally based on streams from 1950 to 2015. "Modified from [Geyer et al., 2017]. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/”

PW generation is expected to reach 12,000 million tonnes by 2050 **(Figure 4)** (Barra et al., 2018), nearly doubling the 6,300 million tonnes generated in 2015, for which only 9% was recycled, with the remainder either incinerated (12%) or disposed of in landfills (79%). For LCs, including SSA, landfilling and incineration are the most common methods of managing PW and by extension MSW (AccessScience Editors; Geyer et al., 2017; Gu & Ozbakkaloglu, 2016; Hopewell et al., 2009). Landfilling can lead to contamination of soil and subterranean water sources. Incineration can result in the release of hazardous chemicals and greenhouse gases (GHGs) into the atmosphere, which might lead to localised toxicity of people living nearby and contributes to global warming (Nkwachukwu et al., 2013). Almeida and Marques 2016 reported that the increase in PW generation goes hand-in-hand with its adverse effects on the health of man and the environment (Almeida & Marques, 2016). Similarly, there has been continuous changes in regulations vis-à-vis the environment (Al-Salem et al., 2009). The proliferation of PW is now a major hazard to many WM municipalities in SSA (Nemade & Thorat, 2013; Rokade, 2012; UNEP/IETC, 2009). In view of all these issues, investigators/researchers, policy makers and non-governmental organizations (NGOs) charged with the responsibility of environmental regulation have now focused on this subject of municipal plastic solid waste management (MPSWM) with the aim of drawing up mitigating measures (The Environmental Association for Universities and Colleges (EAUC), 2016). The main objective of most WM studies is to address issues relating to health, resource recovery; economic and environment benefits of proper WM (Marshall & Farahbakhsh, 2013). Hence, this paper aims to address issues on PW generation and management; the economic and environmental benefits of adequate PW management and the possible sustainable management methods.

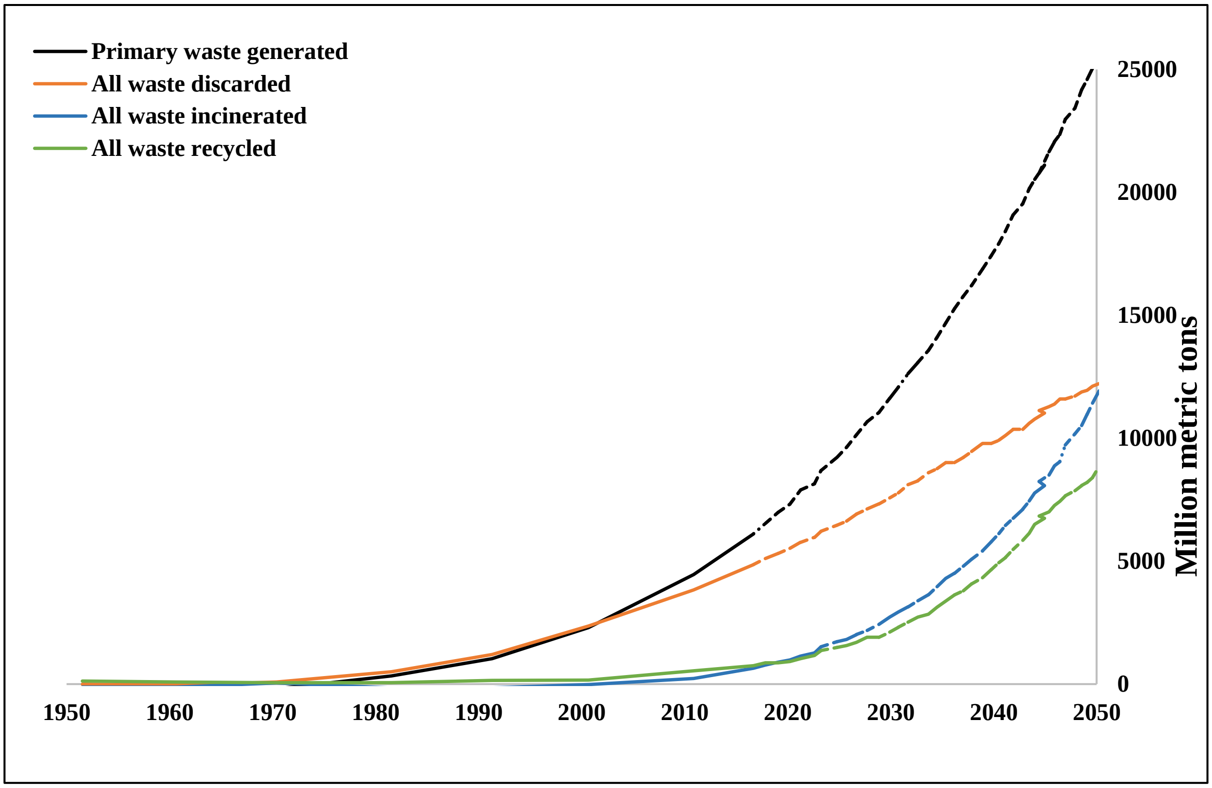

Figure 4: Cumulative plastic waste generation and disposal (in million metric tons). Continuous lines indicating historic figures since 1950 to 2015; broken lines indicating forecasts of historic trends to 2050. "Modified from [Geyer et al., 2017]. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/"

4.1.2. Challenges facing plastic productions and plastic waste management in the SSA

Plastic companies in SSA are confronted with several challenges, one of them is insufficient production of plastic by the local industries which is facilitating the import of more raw materials but the importation does not encourage the thriving of small and medium scale companies since exchange is exorbitant (Construction Materials, 2015; OECD, 2018c). Similarly, the continuous dependence on importations has strangulated many developing economies since there is less revenue to the government coffers. Equally, lack of diversification in terms of raw materials has weakened many sustainable economies (Guzman et al., 2018). In addition, the demand on natural resources for the production of virgin plastic is increasing and there are no adequate facilities for the management of these plastics given that the bulk of them are used for a singular purpose (Babayemi et al., 2018). The usage of singular application plastic has escalated considerably right from when it was first introduced in the 70s (O'Brien & Thondhlana, 2019). This singular usage plastic eventually becomes waste plastic after its end of life but the methods of management of PW are a bit challenging since they are unsustainable (Mularoni, 2016). PW thus leaks and litters into the environment due to changes in consumption pattern, rapid population growth, increased urbanization and economic growth, poor management methods such as; ineffective collection, transportation, handling and disposal (Kumar et al., 2017; Willis et al., 2018). Littering which arises from illegal disposal of PW or from disposal facilities is most common in SSA and is very damaging to the public's health and the environment (Willis et al., 2018). Even while at the disposal sites for over 1000 years because of its non-biodegradable nature, PW escapes into the environment and also releases leachates into the soil thereby polluting surface water, underground water and causes plethora of problems which are injurious to higher and lower animals and the environment (Pavani & Rajeswari, 2014; Webb et al., 2013).

4.2. Current practices with respect to plastic waste management

In a bid to free the environment from increasing PW and to address the burden that PW places on the environment and public health, several strategies are being adopted globally. Some of the approaches employed include, landfilling; primary recycling, secondary recycling (mechanical recycling), tertiary recycling (chemical recycling) and quaternary recycling (energy recovery) (Hopewell et al., 2009). Landfills are an expanse of land constructed using varying strata of soil and waste for the purpose of managing waste (Moscone, 2014). Although, landfilling of MSW is cheaper compared to other WM options, it is the least preferred option in WM hierarchy because it is unsustainable; as PW can remain at the landfills for up 1500 years without degrading (Nkwachukwu et al., 2013; Tansel & Yildiz, 2011). Thus, nations across the globe have been putting stringent policies in place to discourage the setting up of landfills (Oliveux et al., 2015).

Moreover, recycling can assist in minimizing the impact of PW on the environment and in conserving the limited natural resources (fossil fuels) as the process of plastic manufacturing utilizes almost 8% of the total quantity of oil produced globally (Al-Salem et al., 2009; Alley & Alley, 2012; Francis, 2016). Recycling comprises of; primary recycling, secondary recycling, tertiary recycling and quaternary recycling. Primary recycling is an act of reusing plastic materials instead of discarding them after which the contents have been consumed (Grigore, 2017). It is also the direct utilization of uncontaminated waste plastic materials to produce new products with the initial scraps not losing their properties (Selke, 2006). In many parts of SSA, recycling facilities like; buy-back centres, drop-off centres and kerbside collection centres have been established to handle primary recycling (Ayeleru et al., 2016; Harper, 2002).

Furthermore, secondary recycling (mechanical recycling) is the utilization of postconsumer material to produce products with low designs (secondary products) (Al-Sabagh et al., 2016). Mechanical recycling is the most common method of PW recycling and is currently gaining attention in WM (Avolio et al., 2019; Drzyzga & Prieto, 2019). This type of recycling employs mechanical routes in transforming PW into value-added materials (Selke, 2006). Mechanical recycling comprises of collection, sorting, washing, grinding and remelting of PW via extrusion techniques to fabricate secondary products with similar properties like the original materials (Faraca & Astrup, 2019; Ragaert et al., 2017).

Additionally, tertiary recycling also known as chemical recycling (a corresponding process to mechanical recycling) is considered as the utilization of waste plastic as a feedstock for the manufacture of new products (Zare, 2013, 2015). Chemical recycling (CR) is the disintegration of the molecular structure of the polymers via chemical reactions and the outputs of such reaction are usually purified and reused to make the same or similar material (Selke, 2006). CR utilizes depolymerization and decomposition reactions to change polymer into material with a low molecular weight (Manrich & Santos, 2008). In CR, several chemical products are obtained and are in turned used for varied other applications. For instance, in our recent study by Ayeleru et al. 2020, polystyrene waste (PSW) (i.e. expanded polystyrene or polystyrene packaging) is recycled using CR, and organic-inorganic hybrid materials (nanocomposites) were developed. The CR process used is called solvothermal method (Ayeleru et al., 2020). CR is classified into; thermolysis and solvolysis. Thermolysis (thermochemical recycling) operates with a temperature range between 350 °C and 1000 °C. This can be sub-divided into; pyrolysis, gasification and hydrogenation. On the other hand, solvolysis uses solvents and moderate temperatures for the conversion of polymers into new products. This reaction includes; hydrolysis, glycolysis, methanolysis, aminolysis, alcoholysis and acidolysis (Manrich & Santos, 2008).

Finally, the quaternary recycling (otherwise referred to as energy recovery) uses PW for the generation of energy via incineration (Goodship, 2007). Quaternary recycling is not generally classified as recycling since polymers mostly lose their properties in the course of heating to generate energy (Sinha et al., 2010). Besides, incineration on its own creates several environmental issues via the release of toxic substances into the air (Chanda & Roy, 2016). Thus, recycling of

PW in SSA faces some barriers including, immiscibility of polymer materials and contamination of waste plastics which result in polymer with poor mechanical properties and phase separation (Kaiser et al., 2018).

4.3. Drivers of plastic waste generation in the sub-Saharan Africa

Drivers could be described as the anthropogenic activities of man or pressure due to human activities (which could be both social and economic in nature) resulting in negative impact on the environment (Ayeleru et al., 2018; Contreras et al., 2010; Department of Environmental Affairs, 2018; Hoornweg & Bhada-Tata, 2012). As nations of the world are working towards achieving the sustainable development goals (SDGs) as part of Resolution 70/1 of the United Nations General Assembly, the quantity of MSW generated in Africa has been rising incessantly (Dikgang et al., 2012; Hoornweg & Bhada-Tata, 2012). In SSA, the key drivers influencing MSW generated and PW increase are population growth, income level, economic growth, changes in consumption pattern, influx of rural dwellers to urban centres and immigration of economic migrants from surrounding nations and other nations of the world into SSA (Department of Environmental Affairs, 2018; McLellan & Aquarium, 2014). Recent studies have shown that 8 billion plastic bags are consumed in South Africa every year (Dikgang et al., 2012; Gawande et al., 2012; McLellan & Aquarium, 2014). The rise in the consumption of plastic bags has led to the increase in the amount of waste plastics produced and has contributed to acute MSW issue. This PW is growing at an alarming rate while recycling is low (Gawande et al., 2012; Werner et al., 2016). For instance, in 2014, the total quantity of PW generated in South Africa was 1.4 million tons, the amount recycled was 0.32 million tons and the quantity sent to landfills was 1.08 million tons (Andrady & Neal, 2009). PW is now littering the streets because it is often blown away by wind when it is deposited at the disposal site and this has been leading to the death of wild and marine animals (Ayeleru et al., 2018; Science for Environment Policy: In-depth Reports, 2011). Marine animals often ingest waste plastics as the animals frequently mistake plastic debris for food and in many cases when the debris passes through their guts, it settles in their digestive tracts and regularly leads to starvation (Werner et al., 2016; World Health Organization, 2016).

4.4. Authors’ opinion and recommendation on plastic waste reduction and novelty of the study

To reduce the negative impact of plastic waste on public health and the environment, the authors’ personal opinions for a sustainable development (SD) to be attained in SSA are; (i) there must be willingness for a change of our lifestyles since plastics have recently become part of our lifestyles; (ii) the willingness to educate others on the need to reduce plastic usage must also be strong in us; (iii) the use of paper bags instead of plastic bags should be recommended in SSA since paper seems to be more environmentally friendly compared to plastics; (iv) a process that can breakdown plastic bags (polyethylene) using bacteria can be developed since plastic bags do naturally breakdown after a long period, hence this bacteria should be isolated for this task; (v) utilization of reusable plastic cups, plates and bottles should be encouraged at events; (vi) the use of stainless steel or glass straw instead of plastic straw should be encouraged at restaurants and events, hence you can buy one for yourself if you must use one; (vii) the use of plastic materials (and if a must, use a recyclable plastic) should be stopped in your home and do not request for a disposable non-biodegradable plastics at fast food joints; (viii) always take your own reusable jute/green bags for groceries at shopping mall since jute is environmentally friendly, economical and biodegradable and do not request for single-use plastic bags; (ix) discontinue the buying of sachet or bottled water but always move with your reusable bottle to get drinking water; and lastly, (x) discontinue the buying of juice packaged in plastic containers, instead prepare your own; it is much more healthier and it does not only cut cost but also save our environment and public health.

To the best of our knowledge, there has been little or no study in SSA that has focused on plastic waste generation, its methods of management and possible sustainable approaches to manage PW, the possible health risks associated with rapid PW generation, measures to forestall the issues in sub-Sahara Africa region, and an overview of Bisphenol A (BPA) as an additive to plastics.

4.5. Health risks and issues associated with acute generation of plastic waste

Whilst many plastics are considered non-biodegradable leading to accumulation in the environment following disposal, some degrade slowly leading to the release of degradation products into the soil and water table. Furthermore, most plastics contain plasticisers and catalyst residues (from their manufacture) that can leach into the soil (Knoblauch et al., 2018). Therefore, PW can contribute to the production of persistent organic pollutants (POPs) and is also known to act as an adsorbent of POPs from other sources (Lithner et al., 2011; MoEFCC, 2018; Science for Environment Policy: In-depth Reports, 2011). POPs are a major concern for animal and human health, specially, the endocrine systems and reproductive systems (Thompson et al., 2009).

Health issues from plastic products also come from additives, including plasticizers, flame retardants, stabilisers and antimicrobial agents used in the manufacturing process (Erler & Novak, 2010; Farrell & Nelson, 2013; Halden, 2010; Li et al., 2011; Lithner et al., 2009; Lithner et al., 2012; North & Halden, 2013; Proshad et al., 2018). For example, bisphenol A (BPA) is a plasticiser and monomeric building block used for polycarbonates and epoxy resins (University of Cincinnati, 2008), and it is often leached from containers to food sources (Joshi et al., 2019; Papapostolou, 2016). The leaching of BPA is further enhanced through the re-washing and re-use of containers. BPA can inhibit natural hormonal signal in the body and disrupt the endocrine system (Acconcia et al., 2015; Diamanti-Kandarakis et al., 2009; Onundi et al., 2017), and has been linked to a number of disorders and diseases, including ovarian chromosomal damage, decreased sperm production, sudden puberty, fast changes in immune system, type-2 diabetes, cardiovascular disorder, obesity, increased incident of breast and prostate cancer, metabolic disorders, worsened health in women and frequent miscarriages (Konieczna et al., 2018; Lithner et al., 2012; Owczarek et al., 2018; Ribeiro et al., 2017; Schierow & Lister, 2010; Srivastava et al., 2015; Szybiak et al., 2017). There have also been cases of people being contaminated through indirect contact with plastics via ingestion of food wrapped or packaged with plastic packaging materials (Science Daily, 2008). A recent report revealed that people indirectly ingested a fungicide from plastic used to wrap wheat bread, leading to porphyria (Lithner et al., 2011). **Table 1** provides a list of some of the common plastic types and their health challenges.

Table 1: Various plastic types and their associated health challenges

Plastic types	**Uses**	**Toxic chemical present**	**Status**	**Effect/challenges**	**Precautions**	**Ref.**
PETE	Food and beverages containers	BPA, leach antimony	Not safe	Causes carcinogens, vomiting, diarrhoea	Keep out of heat	(Fan et al., 2014; Le et al., 2008; Sohn, 2009)
HDPE	As milk jugs, detergent and juice bottles, toiletries containers, butter tubs	Not confirm	Usually safe and low risk	Stomach ulcers	No definite harm	(Eriksen et al., 2019; Gradus et al., 2017)
PVC	Food wrap, bottles for cooking oil, shower curtains, inflammable mattresses, common plumbing pipes etc.	Phthalates	Not safe	Interfere with hormonal development	Should not be used for food	(Cao, 2010; Made Safe, 2016)
LDPE	To make bottles and bread wraps	Not confirm	Safe	Not recyclable	Reusing them as shopping bags	(Hahladakis et al., 2018; Lahimer et al., 2017)
PP	Yogurt cups, medicine and ketchup bottles, kitchenware etc.	Not confirm	Microwave safe	No known effects	Always microwave using glass containers	(Rochman, 2015; Advancedpetrochem 2016)
PS	Packaging, cups, takeaway materials	Leaks toxic chemicals when heated	Not safe	Takes thousand years to degrade	Avoidance, keep away from heat	(Bernstein, 2009; Hahladakis & Iacovidou, 2018)
Polycarbonate and others	Baby and water bottles, sports equipment, medical and dental devices, CD's and DVD's, computers etc.	BPA	Not safe	Obesity, cancer, endocrine problems in foetus and children	Avoidance	(Cooper et al., 2011; Khan et al., 2019; Schierow, 2011; Schierow & Lister, 2008)

4.5.1. Overview of Bisphenol A (BPA), threat to human life and possible replacement

Bisphenol A (BPA) [2, 2-bis (4-hydroxyphenyl) propane, (IUPAC name)] is one of the profound pollutants in the environment with a devastating effect on public health (Manfo et al., 2014). BPA is widely utilized to produce plastic materials because of its inexpensive, lightweight, transparent, resistant, stable and frangible nature (Eladak et al., 2015). BPA is an artificial compound that is usually employed for producing polycarbonates, epoxy resins, polysulfone resins and polyvinyl chloride (PVC) (Cho et al., 2012; de Freitas et al., 2016; Pelch et al., 2019; Vought & Wang, 2018). While polycarbonates are used in making recycled beverage bottles, new-born feeding bottles, dinnerware, microwave ovenware, eyeglass lenses, automobile parts and in making covers for medical devices; epoxy resins are applied in making coatings for food and beverage containers (Cavaliere et al., 2020; Flint et al., 2012; Pedersen et al., 2015; Pelch et al., 2019; Vandenberg et al., 2007). BPA also acts as a stabilizer and an antioxidant in the manufacture of plastics, the amount of this additive being added to polymers vary from 0.05-3.00 % w/w (percentage by weight) and is dependent on the structure of the additives and the polymers (HahladakisVelis et al., 2018; Ma et al., 2019). The global production of BPA was around ~3 million metric tons in 2002, ~4 million metric tons in 2006, ~5 million metric tons in 2010 and it rose to about ~6 million metric tons in 2011 (Rochester, 2013; Vought & Wang, 2018).

Lately, there have been increasing apprehensions on the harmful health consequence of BPA on human health based on literature, and on other sources which showed BPA is mostly found in household items and industrial products (Rochester, 2013; Schierow & Lister, 2008; Xiao et al., 2019). Taking the above into account, BPA can be ingested via tinned foods, plastic packaging materials and some household effects and the fall out of this has been uncovered in urine, blood, breast milk etc.(Li et al., 2020) Thus, when BPA is consumed, several health deficiencies and disorder for example, feminization of male foetuses, weakening of testes, adjustment of adult sperm boundaries occur in the human body (Manfo et al., 2014).

Moreover, BPA is currently employed extensively in modern-day production processes and consequently, contact with it is most common via polycarbonate plastic materials whilst almost 70% polycarbonates are formed from BPA (Brebbia & Zamorano, 2008; Mielke & Gundert-Remy, 2009). Considering the health issue associated with BPA, there has been growing demand for its possible replacement. Although, researchers have come up with Bisphenol S (BPS) and Bisphenol F (BPF) as probable alternatives, however, based on recent studies, the action of these two chemicals might be analogous to the endocrine disorder which BPA has been known for (Eladak et al., 2015; Herrero et al., 2018; Moon, 2019; Szafran et al., 2017; Trasande, 2017; United States Environmental Protection Agency, 2014; Žalmanová et al., 2016). Nevertheless, researchers have continued to make efforts in getting a workable substitute for BPA, and in view of that, a recent study has proposed Bisguaiacol F, Tetramethyl Bisphenol F epoxy resin, and Tetramethyl Bisphenol F diglycidyl ether as sustainable alternatives. These chemicals have been subjected to laboratory examination and the results have confirmed little possibility to altering estrogenic action (Mancini, 2017).

4.6. Government policies, public participation and opinions; and solutions to plastic waste issues

With regards to the enormous challenges that PW generation poses on public health and the ecological environment, it is therefore crucial to find a lasting solution to abate these issues. Primarily, we considered the various economic instruments available in some selected nations in SSA and government policies with respect to PW management. Next, we assessed the mitigative measures to lessen the impact of PW on members of the public and the environment.

4.6.1. Economic instrument and government policies

For about a decade ago, there has been huge concerns on the need to put policy instruments in place that will assist in regulating the production and consumption of plastic materials so that its impact on public health and the environment can be minimized (Ritch et al., 2009). Two major policy instruments have been in use in some nations in SSA and these include, complete ban or partial ban and fees or taxes on plastic products (Heidbreder et al., 2019; Ritch et al., 2009). Notably among the countries that have implemented these instruments include, Rwanda, Kenya and Uganda in East Africa and South Africa in Southern Africa (Behuria, 2019).

Correspondingly, a program like the "pay as you throw" (PAYT) system can also be implemented for households (the waste generators) to curb their excesses (Lakhan, 2015). PAYT procedures (user pay principle) is a program designed for the purpose of making households to pay in proportional to the amount of MSW generated (Batllevell & Hanf, 2008). This scheme is analogous to water and electricity bills in which households pay according to the amount of usage (Chang et al., 2008; Skumatz, 2008). PAYT system operates on two of the regulatory values of environmental policy and these include, the polluter pays principle (PPP) and the shared responsibility concept. When PPP is employed, members of the public are made to share part of the costs their actions and inactions have created via careless MSW generation, and in general PW generation (Batllevell & Hanf, 2008). In addition to the PAYT, municipalities can create economic incentives in the waste charges by way of incentive models to households who are separating PW from wet waste (organic wastes) and the government can as well enact legislation like container deposit legislation in Australia which is similar to that in the United States for cash refund to consumers who bring plastic containers to designated facilities. Tax credits and discounts can as well be applied to companies that are properly managing their MSW and in the long run separating PW from other waste components (Puig-Ventosa, 2008; Schuyler et al., 2018).

On the other hand, production and consumption of plastics can be regulated via the introduction of institutional legal frameworks to boost recycling. In this way, the recycling rate will increase when manufacturers of products are mandated to take responsibility for their products beginning from the take-back to the recycling and ultimately to the disposal. This is referred to as extended producer responsibility (EPR) which was first introduced in the 90s in Europe (Leal Filho et al., 2019). Several high-income countries (HCs) have enacted laws using EPR in order to increase recycling rates and to achieve a circular economy (CE) (Cao et al., 2016). EPR is one of the useful policy instruments in WM and can be used in the implementation of zero waste (ZW) (MiliosChristensen et al., 2018).

4.6.2. Public participation and opinion towards sustainable plastic waste management

For any SSWM programme (be it government initiatives, stakeholders or policy makers ideas) targeted at tackling the dire issue of PW, involvement of the public is very key for it to be successful (Almasi et al., 2019; Dilkes-Hoffman et al., 2019). Public involvement will help people to appreciate the PW recycling program and subsequently, people will begin to contribute their quota towards its success since they will begin to see themselves as stakeholders in the project (Visvanathan & Kashyap, 2016). To get the public involved in a recycling program, one of the most successful ways is by seeking their opinions regarding its success via the application of structured questionnaires. Several studies on MSW recycling have been carried out using questionnaire survey to evaluate the attitudes and behaviour of the public towards SSWM (Babaei et al., 2015). A recent study by Kirkman and Voulvoulis 2017 showed there is a wide communication gap between the public and the municipalities. The public needs to be well informed as this might help to reduce the rapid generation of PW. Most of the members of the public do not know what happens to their wastes from the point of collection to disposal and many of them even believe that all their generated PW is recycled (Kirkman & Voulvoulis, 2017). Public involvement will assist in bridging the gap that exist since it is the major pathway for which SSWM can be achieved (Xiao et al., 2017). Garnett and Cooper 2014 supported that more engagement of the public will go an extra mile in preventing issues related to policy instrument (Garnett & Cooper, 2014). The issues include, lack of proper understanding of EIs by the public since most people normally assume that EIs is a complicated process and the concern of lack of willingness to pay for WM charges will also be tackled (Gunsilius, 2015).

However, several studies have stated that the level of involvement and awareness of the public towards SSWM and recycling is still at the infant stage. Besides, the level of satisfaction of the public towards their WM services is not encouraging since the WM services received are usually very poor especially for people who resides in rural areas in SSA. Babaei *et al.* 2015 noted that public enlightenment and their satisfaction have not been very vital to municipalities in LCs and therefore suggested that these two factors should be of utmost priority so that WM set objectives can be achieved (Babaei et al., 2015). Keramitsoglou and Tsagarakis 2013 stated that public involvement during the planning and implementation stages of a SSWM program has not been widely promoted exclusively in Africa and thus calls for the need for active engagement of the public (Keramitsoglou & Tsagarakis, 2013). Feo and Gisi 2010 reported that the reason citizens display lack of willingness to source separation of wastes initiative is ignorance (lack of awareness) within the following age group: 14-18 (66.7%); 19-29 (54.4%) and about 30-49, (33%) (De Feo & De Gisi, 2010). It was therefore concluded that the poor MSWM and low recycling rates in Africa and predominantly in SSA are attributable to poor level of engagement and poor awareness campaigns (Mukama et al., 2016).

4.6.3. Mitigation procedures to forestall the impact of plastic waste

In order to mitigate the impact that PW places on man and the environment, the first step is the need for stakeholders to decentralize the production of plastics (Joshi et al., 2019). The plastics industries have identified that plastic production has focused on fossil fuel and crude oil for decades and that has been a major issue to achieving sustainability and the vision of decarbonised industries, but this can be devolved around the utilization of other feedstock like CO_2, CH_4, biopolymers and some biodegradable materials. For instance, substances like CH_4 and CO_2 from landfills can be captured and used for generation of power rather than allowing them into the atmosphere (European Commission, 2011b; Geoengineering Monitor, 2018; Momani, 2009; Palm & Svensson Myrin, 2018; Walker, 2017).

The second step is the need for every stakeholder (including the public, government, non-governmental organizations (NGOs), municipalities, researchers) to change their perceptions about waste plastic. Henceforth, there must be a paradigm shift; rather than seeing plastic as a waste, they should begin to view it as a resource/raw material **(Figure 5)** that can be channeled back into other production processes to boost the economy (European Commission, 2015; Gutberlet, 2010; World Economic Forum, 2016). For instance, the European Commission (EC) has lately set up CE package through which European Union (EU) member states have put finance into the schemes (HahladakisPurnell et al., 2018). The schemes include the kerbside collection (KS) (in which paid contractors and private or charity organizations collect PW directly from households), the household recycling facilities (usually large and are domiciled within communities where households take bulky or expensive waste items for collection) and the last one is the bring sites (typically small in size but are often positioned tactically where there are arrivals of people to the neighbourhood (HahladakisPurnell et al., 2018). This recycling of waste materials back into the economy is referred to as a circular economy (CE) or the “cradle to cradle” (C2C) concept (Twigger

Holroyd, 2016). CE can help us to close the material loops and we can then begin to sustain our natural resources (Dahlbo et al., 2018). The C2C concept is a substitute to the previous linear model of “take, make and dispose” or the cradle to grave (C2G) system of material management/life cycle assessment (LCA) analysis **(Figure 6)**. In the C2G (LCA) system, materials flow from the extractive stage or creation of raw material, through the productive stages/fabrication of products to the final consumers and ultimately to disposal facilities (Ellen MacArthur Foundation, 2013a; Greene, 2011; Ragaert et al., 2017; Twigger Holroyd & Practice, 2018). During these stages, burdens are placed on the natural resources in the form of inputs (e.g. utilization of energy, depletion of virgin materials and using up of recycled resources) to production processes and the output (such as air pollution, water pollution, soil pollution, increased PW or MSW generation, emission of toxic substances to the atmosphere and burning up of recycled resources) from the production processes (Plastic Waste Management Institute, 2016). LCA helps to scientifically, quantitatively and qualitatively evaluate the complete environmental burden of a material from the extraction stages to the end-of-life of the materials but does not provide solutions to any problem created by the materials (Ikhlayel, 2018; Plastic Waste Management Institute, 2016).

The CE deals with the restorative and regenerative of materials through design while keeping product values and improving natural capital; boosting resource yields and reducing risks to public health and the environment (Ellen MacArthur Foundation, 2013b; Kjaer et al., 2018). In SSA, a number of issues would need to be addressed to establish a CE, including: (i), introduction of programs and incentives that encourages citizens to sort and separate PW at source (Babazadeh et al., 2018; Chen et al., 2017; Upadhyay et al., 2012); (ii) a reduction in the dependence on fossil fuels and increasing dependence on renewable sources for plastic production (Abas et al., 2015; European Environment Agency, 2016; Rockström et al., 2017; Verkuijl et al., 2018); (iii) redesigning product to enhance its lifespan and recyclability (Clark et al., 2009; Kelly et al., 2016; Lewis et al., 2017); (iv) complete eradication of waste from the stages of production, and substitution of harmful additives with safer ones (Bougas et al., 2018; OECD, 2018a); (v) a change in government policies and funding to encourage business models that are sustainable (i.e. businesses that will be assisting in the distribution and recycling of plastic materials) (Barra et al., 2018), and; (vi) recycling should be encouraged to avoid leakage of toxic substances into the atmosphere (Ogunola et al., 2018).

Recycling is one methods of WM targeted at minimizing the impact of PW on man and the environment. Hence, educating the public through different media like radio jingles, door to door awareness, campaigns and print media becomes very crucial with the hope that these would lead to attitudinal change and positive perception towards good PW management and at last C2C would be embraced (Nisbet et al., 2009; Vegter et al., 2014). With the adoption of C2C in SSA, economic growth would be decoupled from resource utilization, and toxic substances such as CH_4 (i.e. about 25 times higher than CO_2 in terms of contribution to global warming) and CO_2 which contribute a great deal to the emission of GHGs would drop significantly to around 48% (Bouton et al., 2016; Ellen MacArthur Foundation, 2014). Thus, the CE **(Figure 7)** regime implies that there can be economic growth without increasing burden on the environment through waste generation since there would be no waste again at the production stages (De Medici et al., 2018).

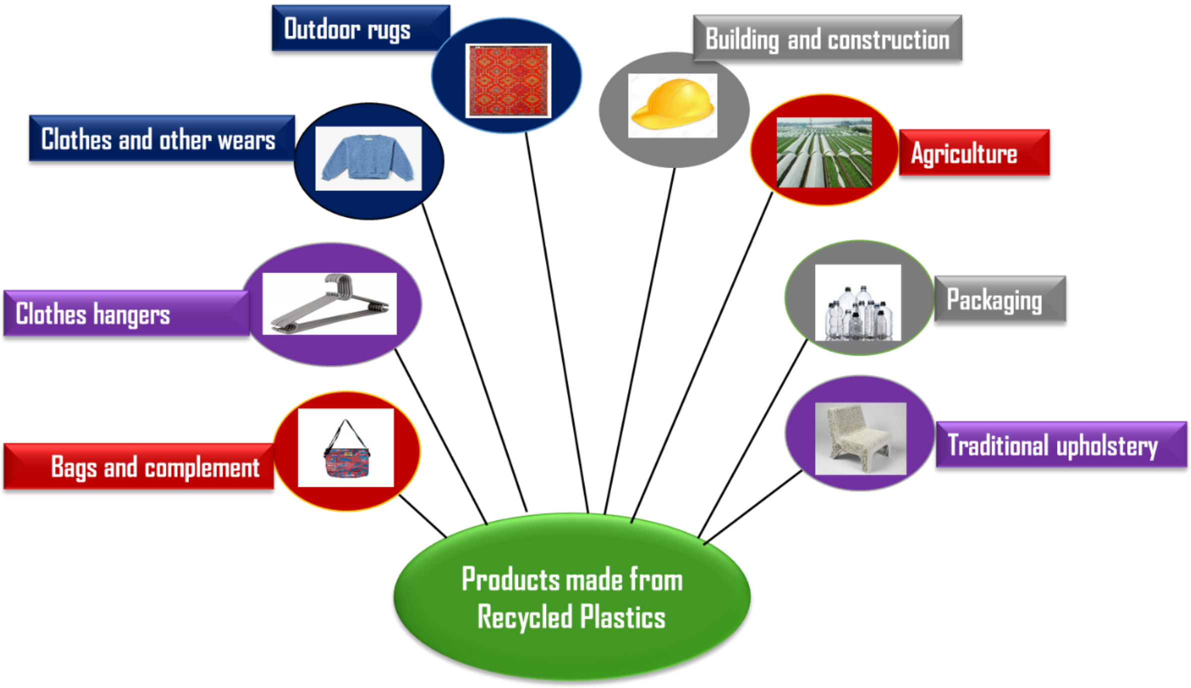

Figure 5: Several usages of recycled plastics

[**Source**: PlasticsEurope, "Plastics – the Facts 2016 (PlasticsEurope, 2016), Accessed on: 8 May 2019]

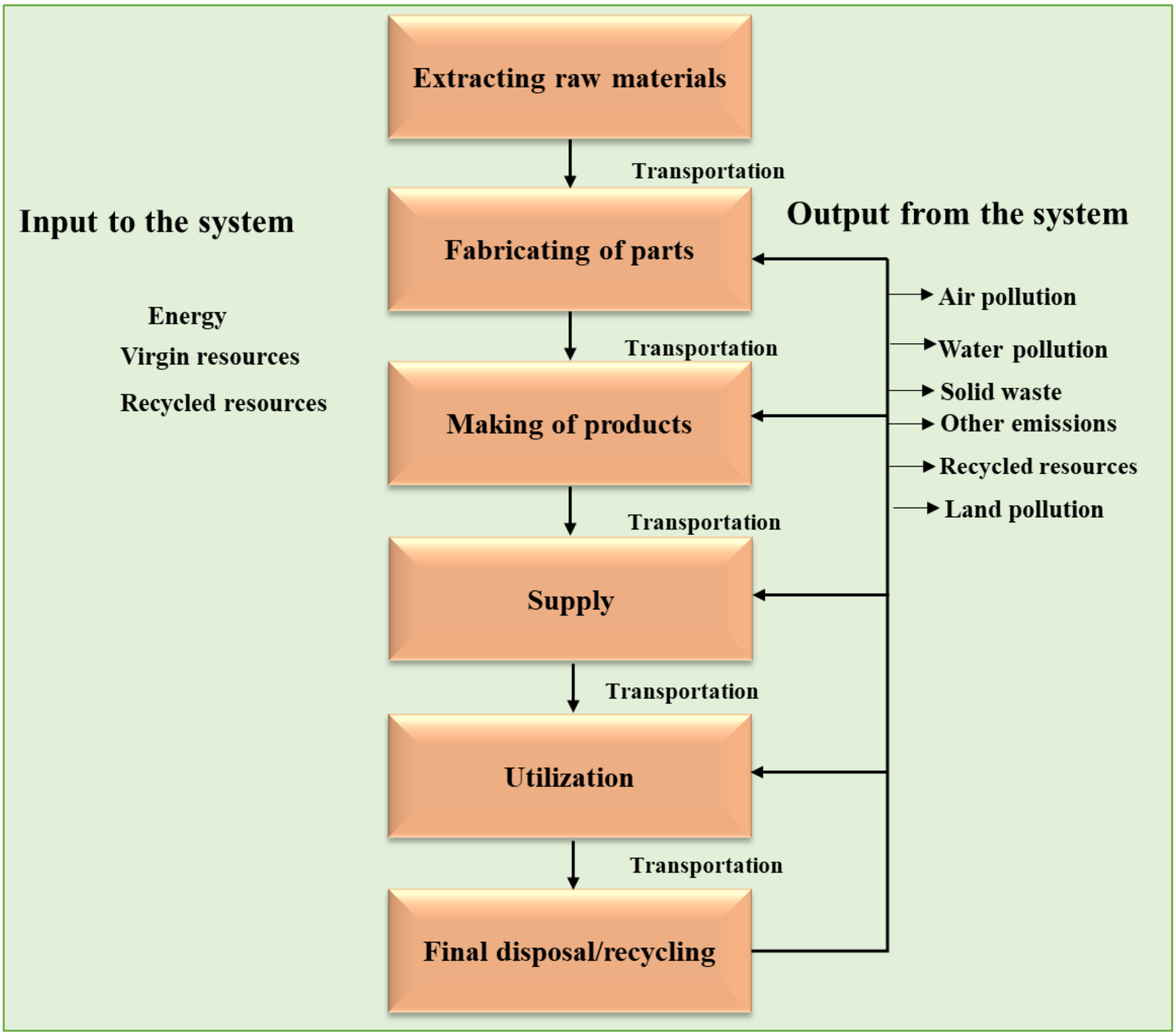

Figure 6: Life cycle assessment of plastic products

Redrawn from Plastic Waste Management Institute (2016)

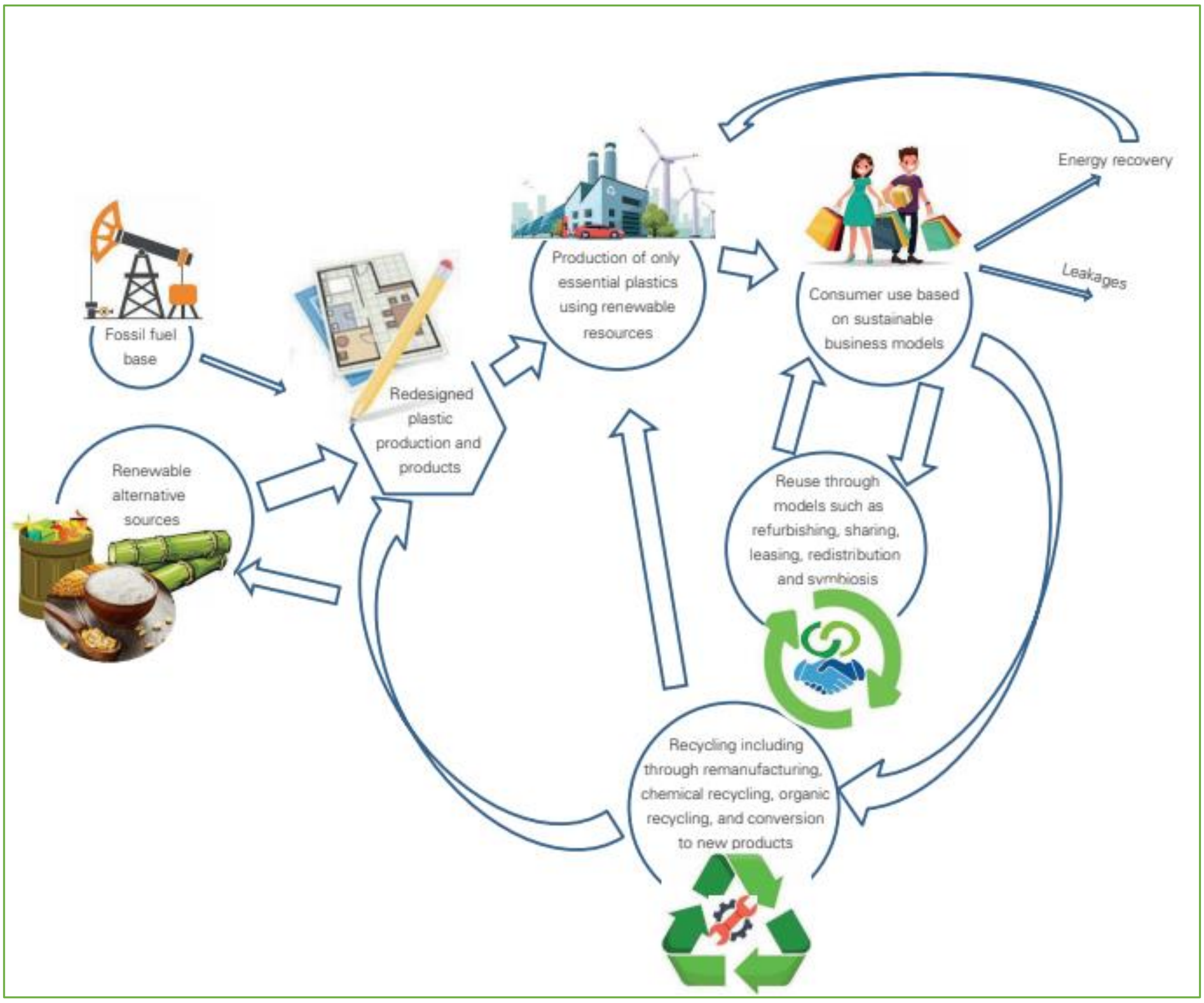

Figure 7: Circular economy resolutions in the plastics production and consumption

[Credit: Barra et.al. (Barra et al., 2018), Accessed on 22 January 2020]

4.7. Benefits of plastic waste management/recycling

When PW is properly managed through recycling, several benefits accrue. These benefits are classified as economic and environmental benefits. Recycling leads to the reduction in the need for landfilling and incineration of plastic materials. PW is completely diverted from landfills and incineration plants and processed into valuable materials used as feedstock for other production processes.

4.7.1. Economic benefits of plastic waste management

Recycling is a cheap disposal alternative which requires less government subsidies and lower taxes (Abdul-Rahman & Wright, 2014). A good PW recycling program will bring about a fundamental change in the utilization of natural resources in a manner that is geared towards economic growth (Banerjee et al., 2014). Job creation has remained a key issue to be addressed in order to achieve sustainable development (SD) in SSA (Voumik & Shah, 2014). When proper PW recycling is in place, raw materials will be readily available for industries; economic growth will be boosted and jobs would be created (New Jersey WasteWise, 2015). More so, efficient PW recycling programs will lead to a cost saving (Department of Ecology State of Washington, 2015). PW is frequently dumped to landfill sites (LSs) where it occupies space decades without degrading and thereby reducing the capacity of LSs which makes the construction of new disposal facilities a topmost issue (Sponaugle, 2014). Typically, billions of dollars are often required for the construction of new disposal facilities whenever the existing ones are about to be closed or when they are not functional. Thus, cost would be saved via plastic recycling (Sultan & Gulnur, 2017; Voumik & Shah, 2014). Moreover, when jobs are created through good PW recycling programs, green economy and sustainability would be achieved in SSA (Sultan & Gulnur, 2017; UNEP, 2011; Voumik & Shah, 2014). The purpose of green economy is to improve the health and social equity of people through the reduction of risks that human activities pose on the environment. A research has shown that an economy which depend heavily on fossil fuel can only create about 1 million jobs, however with renewable energy, new jobs estimated to about 3 million can be created (Citizens' Climate Lobby, 2019; Emas, 2015; Pollin et al., 2009; Richardson, 2018 ; UNEP, 2014; Union of Concerned Scientists, 2017). The concept of green economy does not substitute sustainability since SD, is “the ability of the present generation meeting her “developmental needs without compromising the ability of future generations from meeting their own needs (Emas, 2015;

International Institute for Sustainable Development & United Nations Environment Programme, 2014; Kasztelan, 2017).

4.7.2. Environmental benefits of plastic waste management

There are three main environmental issues that PW contributes towards and for which the impact could be reduced through appropriate WM programs: (i) global warming which occurs through the emission of GHGs, some of which are derived from PW and MSW; (ii) the depletion of natural resources such as fossil fuels for virgin plastic which in the long run becomes PW, and; (iii) damage to ecosystems due to human activities (Diaz, 2011). In SSA, these issues are predominantly caused by incineration and landfilling of PW (Ayeleru et al., 2016; Sawant et al., 2013). Incineration is associated with the release of toxic substances into the atmosphere (Hopewell et al., 2009), including carbon dioxide (CO_2), methane (CH_4), dinitrogen monoxide (N_2O) and NOx and SOx. When these chemicals are emitted into the surrounding, air and water pollution occur, exposing workers and wildlife to toxins and carcinogens (Bejgarn et al., 2015).

When PW is dumped in landfills, it remains at the facilities for many years as the plastic is usually non-biodegradable or very slowly degradable. Even if it does eventually degrade, none of the raw materials used at the initial stages of production are recovered for an extend use (Bandara & Hettiaratchi, 2010; Challcharoenwattana & Pharino, 2015). Furthermore, the degradation products from the plastics may be environmental pollutants resulting in contamination of the soil and water table and causing harm to plants and animals that feed from the soil (Assamoi & Lawryshyn, 2012; Bell & Bremmer, 2013; Hopewell et al., 2009).

With adequate PW management/recycling in place, the amount of harmful chemicals going to the air would be reduced since most of these substances would be captured and used for power generation and other applications (Bunce, 2010; Jambeck et al., 2018; World Health

Organization, 2010). Additionally, the life of aquatic animals will be preserved because millions of marine animals often mistakenly ingest waste plastics which block their throat and cause them to suffocate. Moreover, flooding resulting from blocked drainages due to illegal and open dumping will be prevented, and the body of water which gets dirty as a result of flows from drainages would be kept clean thereby preventing death of aquatic animals (Abota, 2012; Jambeck et al., 2018). In addition, natural resources will be conserved since the need for the extraction of virgin materials or continuous/total reliance on fossil for plastic making will be reduced, and in the end, energy usage during production will be conserved. Finally, recycling will promote the use of recyclable materials over virgin materials and as a result, less effluent will be generated, and at long last, water pollution, land pollution and air pollution will be minimized (Selke, 2006).

4.8. Limitations of recycling

In the same way that recycling has been discussed to have numerous benefits as outlined in the preceding section, it is equally having several shortcomings/cons. These disadvantages include, (i) secondary materials are lost during collection, processing and further processing of recyclables. This is because recycling of materials cannot guarantee total recovery of resource from waste materials (Schneider & Ragossnig, 2014); (ii) inadequate facilities are hindering the recycling of different waste materials especially in the less developed countries (d’Ambrières, 2019; Eureka Recycling, 2009); (iii) contamination of recyclables is constituting some problems such as; sorting of materials becoming extremely challenging and product quality being affected (Al-Salem et al., 2009; Beigbeder et al., 2013; Grosso et al., 2017); (iv) recycling facilities becoming a breeding ground for diverse kind of diseases since additional sites apart from landfill sites are usually created for the processing of recyclables (Renewable Resources Coalition, 2016); (v) recycling programs are usually expensive compared to cost of landfilling (Josephson, 2018); (vi) recycling can result into environmental pollution especially when waste items being sorted leach into the soil thereby contaminating the land and underground water (Gramatyka et al., 2007); (vii) dearth of operational government policies on MSW recycling can as well be a minus (Omodara et al., 2019); (viii) low demand and lack of market for recycled materials in developing countries (DCs) (Wagner et al., 2019); (ix) price changeability between virgin materials and recyclables (Hahladakis & Iacovidou, 2019); (x) the majority of plastic materials are immiscible and contamination of plastic materials often results in poor mechanical properties and phase separation (Faraca & Astrup, 2019); (xi) recycled plastic materials for packaging food products require decontamination of all dangerous items to a satisfactory level that is safe health-wise before it can be used (Eriksen et al., 2019) and (xii) bulk of plastic materials are non-biodegradable which makes recycling a bit of challenge (Niaounakis, 2019; Zhang et al., 2019).

5. Discussion

5.1. Summary

This present review provided a detailed overview of the up-to-date information from literature that addresses the issues of PW globally and predominantly in SSA with a special attention on challenges confronting PW management, current methods of management, health risks and issues and drivers of PW generations in SSA. Assessing over 280 resource materials including, journal articles, government reports, web documents and other unpublished materials, this review has made available a precis of the existing knowledge to researchers, policy makers, stakeholders, non-governmental organisations (NGOs), government and the public. However, it is only 160 published articles that were used for the analysis as shown in Figure 8 where it was observed that more information from literature on plastic waste was available between 2017 and 2019. This could mean more studies were carried out during those periods. Moreover, the review revealed the various possible solutions to PW issues, benefits of plastic waste management and public participation and opinions with respect to PW management.

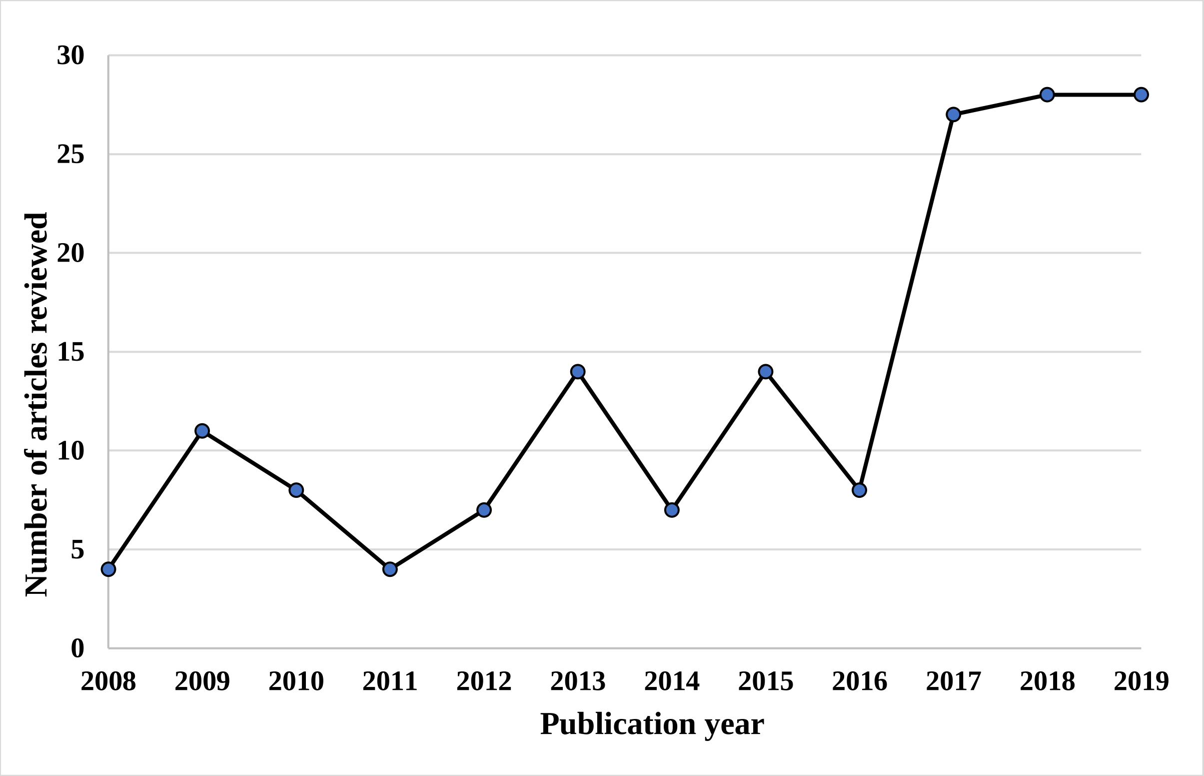

Figure 8: Number of articles reviewed by year of publication.

Note that only articles published between 2008 and 30 November 2019 were captured in this analysis.

In the course of our search for resource materials, it was discovered that discussions on incessant PW propagation and its associated challenges have gained attention in the research world. The bulk of the studies reviewed were conducted in different parts of the world, but all the considerations were connected since PW issues are similar and are of global concern. While several studies relating PW issues have been conducted globally and many of them have focused on European Union and marine habitats (Löhr et al., 2017; Mudgal et al., 2011; Ocean

Conservancy, 2015; Van Sebille et al., 2016; Wilcox et al., 2016), little or none of these studies have placed special consideration/emphasis on SSA which leaves the region with a broader margin/scope for improvement.

This review detailed the challenges associated with production of plastic materials and PW management in SSA. One of the issues is inadequate production of raw materials. Raw materials are rarely available for use in production by small and medium scale enterprises (SMEs). This scarcity has paved ways for continuous importation of raw materials and has adversely affected our SMEs from thriving. The high cost of foreign exchange has been rising steadily and the SMEs are unable to afford the fluctuation in exchange rates and in some cases, the SMEs are not having the capacities to access foreign exchange compared to multi-national industries. Also, the continuous dependent on fossil fuel for production of plastic materials rather than diversification has been causing major environmental problems both to public health and the environment (OECD & Studies, 2015). Similarly, waste collection and disposal in SSA have been characterized with infrequent collection which often result in littering and open dumping. The major causes of these issues were attributed to poor funding and budgeting for WM, lack of distinctive roles among the various arms of government and poor road network which makes waste collection vehicles breakdown frequently (Parrot et al., 2009). Additionally, the bulk of the plastic materials produced in SSA are for single use applications which in the fullness of time, they become PWs. Now, the capacities to manage these wastes responsibly and sustainably in SSA are lacking (OECD, 2018b).

The review also discussed the current practices with respect to PW management which include, primary recycling, secondary recycling, tertiary recycling and quaternary recycling. The most common forms of recycling in SSA are the primary and secondary recycling. Studies have shown that these two methods are not enough to abate the issue of continuous production of PW in LCs. Recent research has been considering the tertiary recycling (chemical recycling) as a promising method and an improvement measure to curb PW issues. In chemical recycling as used in our recent study, PW is used as feedstock to develop value-added materials for varied applications. Here, the concern does not only lie in the recovery of energy through quaternary recycling or in creating secondary materials via mechanical recycling but in the manufacture of value-added materials for advanced applications (Achilias et al., 2012; Rahimi & García, 2017).

As well, the study examined the causes of acute generation of PW generation in SSA and they were attributed to continuous population growth, economic growth, changes in consumption pattern, industrialization, constant influx of economic migrants from rural areas to urban centres and from surrounding nations to SSA region (Gupta et al., 2015). Similarly, the review outlined authors' opinion and recommendation on how to reduce PW in the environment. Some of the recommendations made include, utilization of paper bags instead of plastic bags for groceries, the need and willingness to educate others on PW reduction, the need to begin to reuse plastic materials, utilization of stainless steel straw, the need to devise a process that can break down plastic materials in the presence of bacteria, the need to discontinue the buying of sachet water or bottled water and also, the discontinue of buying plastic packing juice.

Moreover, the health risks and issues associated with PW generation were studied. Some of the challenges which include, contamination of soil and water especially when PW eventually degrades at the dumping sites and leaks toxic substances into the soil. They also contribute to POPs since most plastic materials contain plasticizers and some catalysts. Other health impairments associated with PW are ovarian chromosomal damage, decreased sperm production, sudden puberty, fast changes in immune system, type-2-diabetes, cardiovascular disorder, obesity, increase incident of breast and prostate cancer; and frequent miscarriages (Proshad et al., 2018). Additionally, the review discussed the health implication of BPA and its possible alternative. It was found that BPA is used in almost all plastic materials and when in contact with food items, it is deposited in blood, urine and breast milk and its hazard includes, weakening of testes, adjustment of sperm boundaries etc.

Also, we assessed some of the economic instruments and government policies that have been implemented in some nations of the world as potential measures to reduce the amount of PW generated and increase recycling rates in SSA. The instruments include, complete or partial ban on the use of plastic products (bags), landfill tax (an economical means to manage heterogeneous MSW), deposit-refund systems (a system that oversees and ensure that valued items are not thrown away but recycled). We observed that nations like Rwanda and Uganda in SSA have implemented ban on the use of plastic bags. South Africa has also put fees in place in which consumers pay for plastic bags after shopping. We further recommended PAYT as an instrument in which waste generators will be charged based on the amount of waste generated and those who are not generating PW might be charged less and that could be considered as incentives to encourage high recycling rates. Similarly, EPR and PPP are proposed as other alternative measures to address the issue of PW. For the EPR, manufacturers of plastic products are made to be responsible for their products right from production to the end of life of the materials and for the PPP, they are charged based on the amount of gases released into the atmosphere. Equally, CE package like those established by EC in which PWs are collected directly from households by paid contractors and charity organizations can be adopted. Lastly, education campaign and awareness could also be a major proactive measure since members of the public would only be willing to support recycling when they are informed and possibly when municipal governments get them fully involved in the implementation stages of the project.

Furthermore, the study examined public participation and opinion with respect to PW recycling. It was gathered that the levels of awareness of the public are quite very low, and many members of the public are not satisfied with their WM services. It was concluded that lack of awareness and lack of satisfaction with regards to MSWM could be some of the reasons for the continuous growth of MSW and low recycling rates in SSA. The public would be willing to participate in recycling and SSWM program, but this would only be realistic when municipal government and local authorities take education campaign and awareness very seriously and are also ready to get them fully involved in the entire process. Besides, the review outlined the mitigation measures to minimize the impact of PW on public health and the environment. The measures given include, decentralization of plastic production by using other raw materials other than fossil fuels, the need for all stakeholders to change their perceptions about plastics and be fully involved in recycling.

Finally, the study summarized the benefits that accrue to the public and the environment when PW is properly managed, and the limitations of recycling were also highlighted. These benefits were classified as economic and environmental benefits. The economic benefits include, reduction in the need for landfills, saving of costs for landfills, generation of revenue to the government through recycling, job opportunities to the unemployed and availability of raw materials for industries. The environmental benefits include, reduction in global warming since most of the gases that lead to global warming would be captured and utilized for other applications, reduction in the continuous extraction of natural resources, reduction in water pollution and soil pollution and reduction in the death of marine animals since less PWs would be going into the sea. The limitations of recycling include, loss of secondary materials during processing stages, inadequate facilities, contamination of recyclables, environmental pollution, variability in the price of virgin materials and recycled products, immiscibility of plastic materials etc.

5.2. Future work and recommendation on PW management

With the current global trend in the production and consumption of plastics, it is obvious that PW will continue to grow in the coming years. Fundamental to this constant increment are two major factors; continuous global population growth and continuous innovation in plastic manufacture and products (Vries, 2018). Thus, urgent action and intervention are required to manage PW sustainably in the future. To manage PW responsibly in the future, it is imperative to enhance plastic recycling facilities, improve the demand for recycled plastic materials, introduce PW separation and collections at source and sorting program, and establish a vibrant monitoring structure to oversee the production and disposal of PW (Millicer, 2018). When all these steps are considered, environmental issues caused by poor disposal of PW would be reduced and raw materials will be readily available to manufacturing sectors, and to research and development centres for the development of value-added products from PW. Research in the future may possibly focus on the development of more value-added products from PW (UNEP, 2009). High value materials of better quality compared to the original plastic can be derived from PW. Such materials include greener biofuels, industrial solvents and emollients for cosmetics, and chemicals for plastics (Dove, 2018; European Commission, 2017). In this way, the main objective of closing the loop in material and WM will be achieved since every waste material would have been turned into a resource (Laermann, 2019). Moreover, in many of the nations in Africa, there are scarcity of good potable water and poor sewage and toilet flushing systems. PW can be employed as filtration media in municipal wastewater treatment plant. PW possesses good surface area to volume ratio that is required in wastewater treatment plant (Waymouth, 2015).

5.3. Conclusion

In view of the preceding, the challenges of acute PW generation in SSA can be overcome with the implementation of circular economy. Jobs would be created around PW, the unnecessary burden placed on the natural resources and the environment will be lessened; the negative impact of increased PW generation on public health will be reduced and, in the end, greener environment would be achieved. Also, raw materials will be readily available to industries and it will provide an alternative source of revenue to the governments. In addition, the cost of importation of resins will be reduced thereby creating opportunities for the local industries (SMEs) to develop; and in this way, the continent of Africa will begin to move towards sustainability.

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Paper 2: Potential innovative technique for the management of polystyrene waste in South Africa

(Accepted in Taylor & Francis & CRC)

Abstract

Polystyrene wastes include take-away plastic wastes and expanded polystyrene wastes (EPSs) (packaging items for materials such as refrigerators, washing machines, electronic gadgets etc.). The management of polystyrene wastes is a major source of concern since these wastes are non-biodegradable and the current methods of disposal are also unsustainable. Moreover, there are scarcity of land for use as disposal sites, especially in major cities owing to rapid industrialization via urbanization and rapid rural-urban migration. Despite this, there are scanty data bank on the various types of plastic wastes viz a viz: polystyrene wastes generated in many of the developing countries (DCs). Hence, a need to have a documentation on the amount of polystyrene waste generated globally within the last decade and half ago. This review presents an overview of solvothermal processing techniques via the incorporation of inorganic precursors into polymer matrix for the recycling of polystyrene wastes.

Keywords: chemical recycling, polystyrene waste, landfilling, incineration, solvothermal method, South Africa

3.1. Introduction

There are four groups of materials all over the world. These materials can be classified as metals, ceramics, polymers and composites (Kam & Kueh, 2015). Polymer Plastics (PPs) have been employed in diverse applications, which has led to its exponential increase in the recent years. Polymers itself are materials comprising of structural units that occur repeatedly in which each of its units is obtained from a compound known as monomer (Tur & Trivedi, 2015; Tur & Trivedi, 2014). Polymer could be divided into two which include, the thermoplastic and thermoset and once additives are combined to them, plastics are formed (Kam & Kueh, 2015). Plastics are materials made up of high molecules polymers which comprise of carbon and hydrogen formed from petroleum and natural gas (Plastic Waste Management Institute, 2009). Plastic can be grouped into seven classes (**Figure 1**). Plastics are non-biodegradable material, with artificial synthetic polymers; its structure does not occur naturally (Kržan, 2012). The global plastic production is in the tenth of million tons annually. This growth has called for holistic approach for efficient, effective and sustainable technology for the recycling of the waste polymer plastics (WPPs) generated after its first application or usage (Geyer et al., 2017). Presently, incineration and landfilling are methods extensively used for the disposal of WPPs, only a fraction of waste generated from PPs have been recycled by material recycling, thermal energy recovery or hydrothermal/solvothermal process (Antelava et al., 2019; Awasthi et al., 2017). Therefore, new technologies for WPPs recycling are expected to develop since the conventional methods are having issues with regards to recycling and on the data of the amount of waste generated.

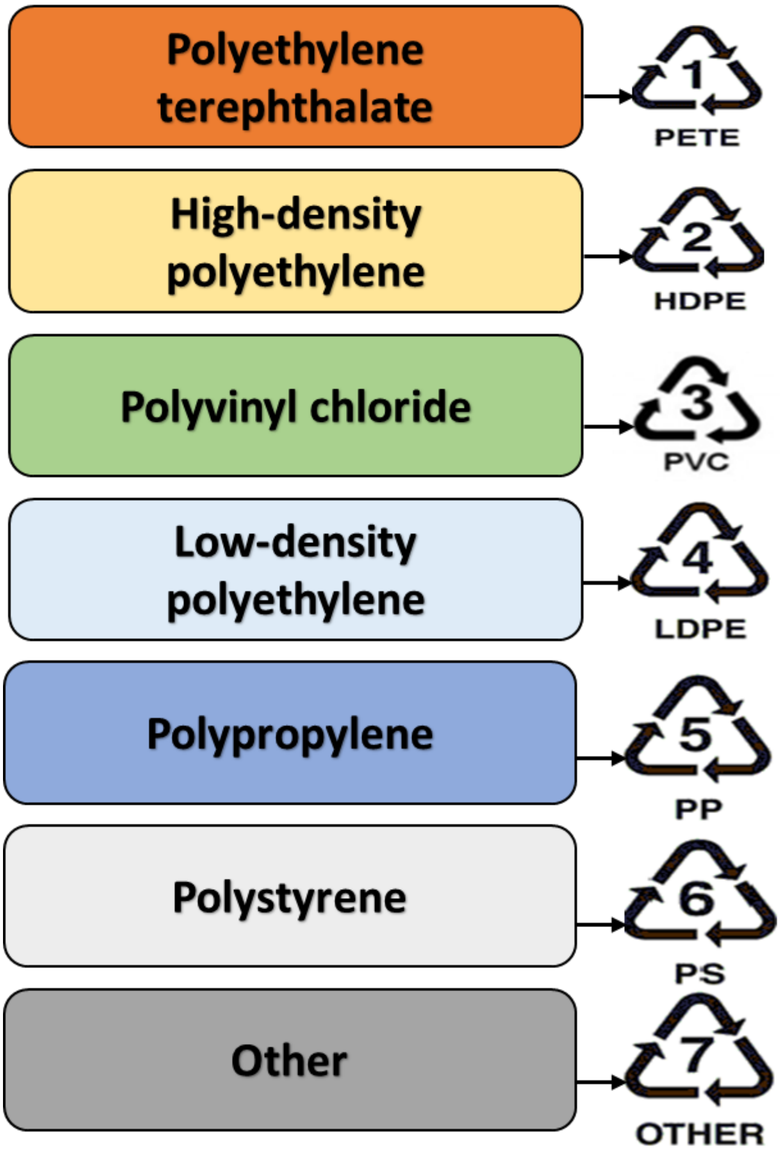

Figure 1: Various kinds of plastic recycling codes

3.2. Overview of polystyrene

Polystyrene (PS) has been in used globally as far as 1839 and is the oldest and most utilized aromatic thermoplastic derived from styrene, an hydrocarbon family (Hansen et al., 2015; Lynwood, 2014). PS is a material that is thermally cracked into aromatic hydrocarbons because of its aromatic essentials properties (Hussain et al., 2012). It is a multipurpose plastic material employs in many applications such as packaging of household items, electronics packages, packaging of food items, laboratory wares and in many other purposes (Al-Maaded et al., 2012; American Chemistry Council, 2014; Samper et al., 2010). A recent study has also shown that PS has been utilized as packaging materials since the early 50s (Block et al., 2017). PS is the type 6 plastic (**Figure 2**) which can either be rigid or foamed, and has potential applications in many areas (Cleanaway, 2018). The rigid PS is employed as containers for yoghurt drinks, plastic spoons etc. The foam aspect of PS is the expanded polystyrene (EPS) which is utilized as cups for hot teas or coffees, packaging for refrigerators or electronic packaging. It is made up of approximately 96% air and 4% of plastic (Cleanaway, 2018; UNEP, 2018). The global growth rate of PS production has been steadily with about 1.4% rise annually since 2000 and its market demand had reached ~15 million tons since 2010. The market demand for PS has been projected to hit ~24 million tons by 2020 (Hansen et al., 2015; Intelligence Global Business, 2012). PS is mostly categorized as crystal PS (CPS) or general purpose polystyrene (GPPS) because of its sparkling appearance or as high impact polystyrene (HIPS) because of its brittleness (Amaniampong, 2015; Hansen et al., 2015). The GPPS is used for making video cassette cases and other materials (Cleanaway, 2018). PS is usually formed through suspension or solution polymerization of styrene monomers obtained from petroleum (Abota, 2012; Amaniampong, 2015; Ampofo, 2015; Chemicals and Petrochemicals Manufacturers' Association, 2012).

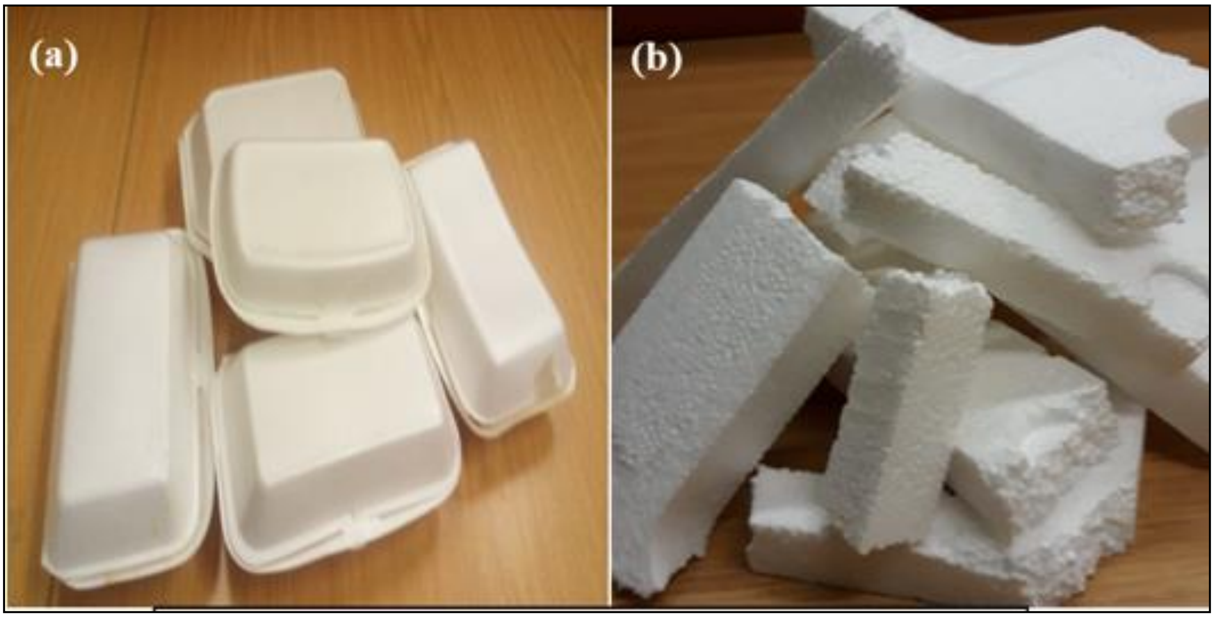

Figure 2: (a) Polystyrene containers; (b) Polystyrene packaging

However, the advent of PS on global market and its application in wide range of product packaging which include; production of widespread of products of low-cost, high-performance, energy saving, and sustainable development has led to the acute growth rate of PS (Vilaplana & Karlsson, 2008). The combination of PS with additives and colourants has been leading to the production of several products like toys, automobile parts, electronics etc. (American Chemistry Council, 2014). The bulk of this PS material has a single use application from which it eventually becomes a waste otherwise known polystyrene waste (PSW) (Global Alliance for Incinerator Alternatives, 2013; Mo et al., 2014; Verma et al., 2016; Watson, 2016). The continuous growth rate of PSW is now an issue of concern globally since consistent information on municipal solid waste (MSW) generation are usually scanty or unavailable in low-income countries (LCs). Moreover, places where MSW data are available, the statistics are usually unreliable, hence regular waste characterization activities on different MSW streams particularly, plastic waste (PW), becomes very necessary (AbdAlqader & Hamad, 2012; Miezah et al., 2015). From the recent waste composition studies conducted in South

Africa, it was observed that the amount of PSW generated was not reported but was documented that the recycling rate of PSW has been increasing considerably since 2016. Furthermore, a survey conducted between 2013 and 2015, reported that, the rate of recycling of PSW grew by 106% but there was very little evidence to support the claim (Infrastructure news, 2017). The significant increase observed in one of their findings was said to be due to public enlightenment on the need for recycling and the need for rapid creation of end markets (ESI Africa, 2018; Infrastructure news, 2017).

In the same vein, studies conducted by Ayeleru et al. (2016) and Ayeleru et al. (2018) in the City of Johannesburg, South Africa, corroborated the previous reports that there are no records or separate data for the PSW generated from the total volume of PW streams consumed. The studies only reported that approximately 27% of the overall amount of MSW generated were plastic wastes (PWs) (Ayeleru et al., 2016; Ayeleru et al., 2018). In addition, a study has reported that ~0.5 million tons of PWs were generated in Ghana annually but none of these wastes were collected. These are clear pointers that there are no records for PSW generated in many nations in Africa including South Africa (Kortei & Quansah, 2018). Similarly, some studies in Ghana reported that out of the total volume of PWs generated, only 2% were recycled while the remaining were disposed of to the landfill sites; some were dumped by the roadside and allowed to litter the street, while the remaining were thrown into the drainages (B&FT Online, 2016; Lambert & Sabutey, 2016). Ackah et al. (2012) reported that PWs accounted for about 16.5% of the total MSW generated in Accra, the capital city of Ghana but there was no statistical data to quantify them into different PW streams. (Ackah et al., 2012), Furthermore, a recent study conducted at the University of Lagos, Nigeria by Adeniran et al. (2017) only focused on the percentage compositions of polythene bags and other plastics (i.e. 24% and 9% respectively), there were no records for other PW streams including, the PSW (Adeniran et al., 2017). Adekomaya and Ojo (2016) reported only the total percentage of PWs

(57%) from total MSW generated in Lagos State, Nigeria. (Adekomaya & Ojo, 2016). Imam et al. (2008) in their study carried out at various locations/outlet of the Federal Capital Territory (FCT) of Nigeria, reported the percentage total amount of PWs generated, there are no data to classify PW into streams (Imam et al., 2008). Abur et al. (2014) in their study also did not report the percentage compositions of different type of PWs (Abur et al., 2014). Gakungu et al. (2012) carried out a study in over forty tertiary institutions in Kenya, but only revealed the overall compositions of waste generated; there were no data for the amount of PWs generated nor the percentage of PSW (Gakungu et al., 2012). All the above reports have supported other previous studies that there are little or no records for individual PW components in the developing countries (DCs), specifically in South Africa. To the best of our knowledge, there has been little or no study that has focused on the recycling of PSW via chemical recycling technique (U.S. Environmental Protection Agency, 2015).

3.3. The 4R of polystyrene waste to Zero waste

There have been numerous conceptual fact about PS waste management. Firstly, it has been the 3Rs (reduce, reuse and recycle) concept. The 3Rs was said to be achieved when priority are rightly placed in a way that can assist in cutting back the amount of PS consumption. The 3Rs is often referred to as the hierarchy of waste management (WM) and has been promoted in many nations of the world, including in Japan (Abdul-Rahman & Wright, 2014; Green Coast, 2019; Organisation for Economic Co-operation and Development, 2019; Wichai-utcha & Chavalparit, 2019; Yolin, 2015). The 3Rs later graduated to 4Rs (reduce, reuse, recycle and recover) when the former was no longer effective enough to address the issue of acute MSW generation, particularly the PSW. The reduce concept is to decrease waste in the prodcutive stage and to utilize resources efficiently. The resuse idea is to put into use again what has been considered should be discarded. This idea was adopted to change the properties of the waste item to a better form. The recover model is employed to recoup resources from materials that ordinarily are to be thrown away and the innovative methods employed is the chemical recycling (City of Belmont, 2019; International Institute for Sustainable Development, 2013; Sadi et al., 2012; Skanska, 2012). In recent times, the development of materials with enhanced features and functionalities is gaining wider attention in the field of material science and interface of chemistry (Katagiri, 2017; Pyun & Matyjaszewski, 2001). One of these materials is the hybrid nanocomposite (NC) that can be developed via the incorporation of organic polymer into inorganic materials to form an outstanding novel material (Pyun & Matyjaszewski, 2001). Generally, hybrid organic-inorganic materials depict a boundary between two worlds of chemistry where each of them offers a profound contribution to material science since the properties of each will be of immense benefits to material science (Gomez-Romero, 2001).

Because of the numerous issues confronting many nations of the world with respect to production and consumption of plastic materials, it has become very crucial to design a new and functional hybrid materials or nanocomposite (NC) with enhanced properties from PSWs since this will help to reduce the excessive waste polystyrene in the environment (Krasia-Christoforou, 2015). The NC comprised of two or more materials with diverse physical and chemical properties to form a novel material, with one of these materials having a grain size range of 1-100 nm (Akpan et al., 2019; Govindaraj et al., 2004; Lateef & Nazir, 2018). NCs have large surface area that can support interfacial connections alongside polymeric environment when compared to traditional fillers. This brings about the enhancement of the properties of polymers. Recently, organic and inorganic materials have gained attention extensively in the development of NCs owing to their special features (Mallikarjuna et al., 2005; Song et al., 2004). The organic materials include; plastic materials with unique properties such as physical, thermal and mechanical properties which made them good candidates for varied applications (Grigore, 2017). In a bid to lessen health and environmental issues connected with poor disposal of waste plastics, several studies have lately incorporated inorganic precursors into polymer materials to produce polymer composites of better properties compared to the original materials (starting materials) (Ali & Venkataraman, 2014). The incorporation of inorganic precursors into the polymer composites to produce NCs is very crucial to numerous applications (Barry et al., 2018). The development of NCs from PSWs can now serve as a sustainable alternative since landfilling and incineration of MSW pose serious threat to public health and the environment. Hence, PSW which was once regarded as a problem can now begin to realize its potential applications in different fields, thereby providing solutions to the issues of pollution arising from poor PW management (Aslam & Er. Shahan-ur- Rahman, 2009; Bandara et al., 2017; Krasnov et al., 2010; Patil & Khurd, 2015; Yunus & Fauzan, 2017).

3.4. Current methods for the development of value-added materials from recycled polystyrene

NCs as shown in (**Figure 3**) are materials of superior value to industries and have been prepared through various routes during the last decades (Oliveira & Machado, 2013). Some of these methods include; the sol-gel, melt blending, in-situ polymerization, solution blending, direct compounding and melt intercalation (Khan et al., 2016). However, most of these techniques have huge limitations that are preventing them from being scale up for commercialization. Some of the challenges include; high temperature for the decomposition of polymers which may affect the processing conditions of the products and could decompose polymer itself, poor dispersion of polymer into the polymer matrix, intricacies encountered in the choice of solvents, formation of aggregates which may not allow homogenous dispersion of polymer into the matrix and sometimes heat is required in some of the methods. All these could also be major drawbacks and could also hinder commercialization of the techniques (Filippi et al., 2007; Paszkiewicz & Szymczyk, 2019; Ravichandran et al., 2018; Ucankus et al., 2018).

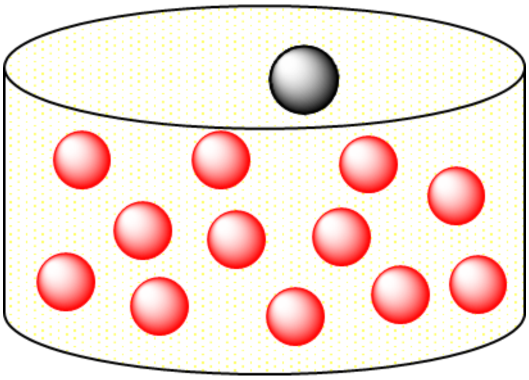

Figure 3: Organic-inorganic hybrid nanocomposites

3.5. Solvothermal and hydrothermal methods

Hydrothermal technique of material synthesis was established following the second world war (Buisson & Arnaud, 1994). The first study on hydrothermal process was conducted by Schalfthaul around the mid-19th century (Suchanek et al., 2004). Hydrothermal method is closely related to solvothermal process. They are both appropriate for the development of novel materials (Tareen, 2013). Hydrothermal technique is usually described as crystal synthesis/growth that employ single or diverse phase reactions operating under a high temperature and high-pressure water conditions from materials that are not soluble at room temperature and pressure (Hayashi & Hakuta, 2010; Riman et al., 2002). Hydrothermal method is different from solvothermal technique, while hydrothermal utilizes aqueous solvent, solvothermal synthesis method uses non aqueous solvents for material synthesis (Riman et al., 2002). The merit of solvothermal/hydrothermal method over other conventional and non-conventional techniques include, the ease of conversion or scaling up to commercial application, cost-effectiveness and all ceramics such as powders, fibers, polymers etc. can be all be synthesised via solvothermal/hydrothermal method (Riman et al., 2002; Suchanek et al., 2004). Hydrothermal/solvothermal reactions are usually done in a sealed reactor (otherwise known as autoclave) or high-pressure bomb. The autoclave comprises of Teflon cup or can made from Teflon whose purpose is to shield the autoclave from corrosive solvents (Li et al., 2016). **Figure 4** showed the autoclave reactor and **Table 1** showed the commonly used reactors for hydrothermal/solvothermal methods.

Figure 4: A hydrothermal autoclave reactor

Table 1: Generally utilized reactors for hydrothermal/solvothermal methods

Type	Temperature (^{o}C)	Pressure (bar)
Quartz tube	250	6
Cone closure	750 to ~1,150	4000 to ~13000
Welded closure	400	3000
Modified Bridgman autoclave	500	3700
Piston cylinder	1000	40000
Opposed diamond anvil	>2000	500000

Source: (Li et al., 2016)

Currently, there is a need for combinations of diverse techniques which are very common among researchers for optimum result and the hydrothermal method is not an exception on this drive. Hydrothermal hybrid techniques have been reportedly employed for synthesis of materials (including nanomaterials i.e. NCs) and chemical compounds, mainly inorganics. Moreover, in order to enhance the reaction kinetics optimally or the ability to make new materials, a great amount of work has been done to hybridize the hydrothermal technique with microwaves (MW) (*microwave-hydrothermal processing)*, electrochemistry (*hydrothermal electrochemical synthesis*), ultrasound (*hydrothermal-sonochemical synthesis)*, mechanochemistry *(mechanochemical hydrothermal synthesis)*, optical radiation (*hydrothermal-photochemical synthesis)*, and hot-pressing (*hydrothermal hot pressing*) (Suchanek & Riman, 2006).

Hydrothermal method itself, microwave-hydrothermal and microwave-solvothermal methods are, in particular, truly low-temperature methods for the preparation of materials of different sizes and shapes. These methods save energy and are environmentally friendly, because the reactions take place in closed isolated system conditions. The NC materials can be produced in either a batch or continuous process using the above methods (Iwaya et al., 2008; Kharisov et al., 2012). In our recent study by Ayeleru et al. (2020) the solvothermal technique was utilized for the development of nanocomposites from recycled polystyrene materials via the incorporation of metallic precursors into polystyrene matrix and the results obtained were excellent showing an economical novel means of recycling PSWs via chemical recycling with little or no impact on public health and the environment (Ayeleru et al., 2020).

Conclusion

The paucity of reliable data can be problematic for researchers in conducting research. However, point attention on this issue with the intention of profferring solution to it goes a long way in solving the challenge. PS waste generation, application, waste management and technology involved in their production has been disscussed. Emphasis were placed on new method or process technique of their production which include hyrothemal/solvothermal process. More work can be done on detail analysis on processing method from different countries alongside detailed waste management method.

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CHAPTER THREE

INVESTIGATIONS PUBLISHED FROM THIS STUDY

3.1 Precise

Effect of the inclusion of nanomaterials into the polymer matrix, compositional and structural characterization; morphological characterization, thermal properties and mechanical characterization of organic-inorganic NCs was studied. The study employed solvothermal method of synthesis for the development of polymer based NCs using recycled polystyrene (rPS) and inorganic metallic precursors under different impregnation ratios. The experimental comprised the utilization of polystyrene wastes (PSWs) for the manufactured of NCs for varied applications. Nanoindentation technique was carried out for the assessment of the mechanical strength of the materials and thermal property (TGA and DSC) for the enhancement of thermal properties and phase changes of the hybrid NCs. Other characterization techniques conducted include, XPS, XRD, FTIR, SEM, TEM and DLS, BET, NMR and GPC to study other properties of the synthesized hybrid NCs.

3.2 Summary of the developed articles

About four (4) journal articles and a book chapter were produced from this study, where some were already available online from peer-reviewed reputable international journals. These articles and a book chapter were organized in a way that showed that the specific goals of this research were accomplished, and research problems all resolved. All the research articles comprised of background/introduction, experimental section made up of materials and methods, data from the investigation and critical discussions of the data. Inferences were extracted from the data obtained. Funding bodies were duly acknowledged and relevant and up to date literatures were cited. Some of the articles also contain supporting information or appendixes. Summaries of all the articles were outlined in the following section.

Paper 1: *Challenges of plastic waste generation and management in sub-Saharan Africa: A review* ***(Published in Waste Management)***.

PW generation is now global matter since its growth rate is increasing steadily as population of people rises and there have not been corresponding facilities to manage this waste responsibly and sustainably especially in low-income countries and studies on this subject are very few particularly in sub-Saharan Africa. These have made this area of research to be a hot topic of interest that needs to be thoroughly investigated. In view of that, literatures on previous studies were searched to make information available on the issues associated with plastic production and plastic wastes generation in Africa. The areas of emphasis in this literature review include, an overview of issues connected with plastic waste management, current practices with respect to plastic waste management, public opinion, government policies, effect of plastic waste explosion on man and his natural surroundings, economic and environmental benefits of proper plastic waste management, limitations of recycling and critical discussion on current processes. Moreover, potential solutions and mitigating measures to forestall the damaging effect of plastic waste on public health and the ecosystem were highlighted in this review.

It was inferred from the study that rapid consumption of plastics result in high rate of plastic wastes propagation which leads to damaging environmental and health issues. When these waste plastics are managed properly or sustainably, several economics and environmental benefits can be derived. The economic benefits include, provision of jobs for the unemployed youths, source of revenue to the government and cost saving with respect to construction/reconstruction of landfill facilities. Moreover, the environmental benefits include, minimization of global warming, cutback in fossil fuels usage, decrease in amount of toxic substances going into the air and decrease in air, water and land pollutions.

Paper 2: *Potential innovative technique for the management of polystyrene waste in South Africa* ***(Accepted for publication in Taylor and Francis & CRC Press)***

Polystyrene waste generation is increasing daily in South Africa since every fast food joint, restaurants, student cafeteria and supermarkets; shopping malls and departmental stores employ it for packaging either cooked or raw food. It is equally used in some events for serving food to the guests. Because of its numerous applications, this waste has continued to increase daily and there has never been a better way of recycling especially in South Africa, unlike in other places such as Australia, United States of America etc. where there are recycling facilities dedicated to polystyrene waste. On account of the lightness of this waste, it has now become a social menace in our environment since it is easily blown away by winds and litters the street (or called "national flower") and often block drainages during raining season. In this Chapter, several techniques for the preparation of nanocomposites using organic polymer and inorganic precursors were highlighted. It was drawn from the study that most of the techniques highlighted were with one or more limitations which hinder them from being to commercial scale. It was reported that recycled polystyrene/polymer waste can be best recycled via solvothermal technique since it is economical, low temperature is required and be easily scale up. It was therefore concluded that solvothermal method can be an alternative means of lessening the waste plastics from the environment and reducing its negative impact on the public.

Paper 3: *Recycling attitudes and students' behaviours towards municipal solid waste management at the University of Johannesburg, South Africa* ***(Under review in The Journal of Solid Waste Technology and Management)***

Municipal solid waste management is a burden across the globe, particularly in developing nations because of the continuous adjustments eating habits, incessant economic and industrial growth; and constant influx of rural dwellers and economic migrants to cities leading to rapid population growth. As cities expand, the volume of waste also increases but with no adequate facilities to manage it sustainably. Aside, the majority of the members of public are not well enlightened on the proper ways of handling household municipal solid wastes. Due to this improper handling, many communities in Africa have started experiencing major outbreak of incurable diseases (e.g. dysentary, leptospirosis etc.) and several natural disasters such as flooding, soil contamination, water contamination etc. have also been occuring in our environment. To avert these issues, all stakeholders (including, informal sectors, formal sectors, municipalities, non governmental organizations, research institutions, academic institutions and members of public) need to be informed on a recycling practice since several people are unaware of the damaging impact that their activities pose on other people and on the natural environment. This area of research on waste education has not been carefully explored especially in South Africa. Hence, it becomes very crucial to carry out this study to sensitize the public that is an urgent necessary for a total involvement/participation.

In this study, the attitude and behaviour of students were evaluated using the students of the University of Johannesburg as a sample. A structured questionnaire was designed via the Google form platform online survey and paper-based copies and were given out to a random sample of students across the four campuses of the University. A logistic model prediction was employed to assess the attitudes and behaviour of the students towards a sustainable future. Based on the study, a good number of the students were not properly enlightened with regards to their health and environment issues since around 70% of the respondent did not know where their collected solid wastes are taken being to for final disposal and another 72% are not currently separating their solid wastes into different waste streams.

Paper 4: *Novel green route towards synthesis of recycled polystyrene-based nanocomposites via solvothermal technique* ***(Under review in Pollution Research)***

The pursuit to develop value-added materials with enhanced properties as a way of ridding the excessive plastic waste from the environment brought about hybrid nanocomposites manufactured from plastic waste. Polymer-based nanocomposites are polymers having matrices within a range of 10 and 100 nm. They are made via the impregnation of organic polymers with inorganic metallic precursors and by way of painstaking material selection, design and synthesis which have given them a superior capability of exhibiting excellent properties. Due to the uniqueness of their characteristics, these synthesized hybrid materials are facilitating improvement of features of nanocomposites and these have made them gained wide attention in research world in recent times. Moreover, their exceptional properties have given them a high possibility for applications in fields like construction, automotive, sport, marine, energy, electronics, medical, aeronautics, and in consumer goods. However, there are little studies on this area of research and this has made this study to be of interest especially in curbing some of the issues associated with rapid plastic wastes propagation in sub-Sahara nations.

In this study, polystyrene-based nanocomposites were developed via solvothermal method as a way of upcycling waste plastics. The processing conditions were at a temperature of 250 ℃ and 3 h. The materials were studied by different characterization techniques XPS, XRD, DLS, TGA, DSC, BET etc. The neat polystyrene materials (untreated or thermally treated) were also characterized by NMR and GPC to evaluate the chemical shift and the molecular weight distribution in the polymer repectively. Results obtained showed that the inclusion of nanoparticles within the polymer matrix showed an enhancement in the thermal properties of the nanocomposites. Furthermore, the FTIR spectra did not showed the formation of any new peaks which is an indication that there was no strong interaction or chemical bonding between the functional groups of the nanocomposites and the polymers. It was therefore concluded that no chemical bonds were created between the synthesized materials and the functional groups of polystyrene.

Paper 5: *Nanoindentation investigations and characterization of hybrid nanocomposites based on solvothermal process* ***(Published in Inorganic Chemistry Communications)***

The successful manufacture of hybrid organic-inorganic nanocomposites from polymer wastes has necessitated the need to evaluate the mechanical and thermal properties of these materials since they are envisaged to play diverse roles in varied applications including energy, construction etc. The mechanical and thermal characterizations of hybrid nanocomposites are very crucial in determining the integrity of polymeric materials. Mechanical properties are often challenging to estimate because of the major influence of the underlying substrate. Polymeric materials are prone to failure and detection of this failure is often difficult. Hence, mechanical characterization can be employed to detect this early stage of the life of polymeric structure before catastrophic failure or tragic colapse is experienced. Nanoindentation technique can be utilized for the examination of the mechanical characteristics (such as load-displacement curves, displacement-time curve, nanohardness, elastic modulus etc.) of materials. However, up till now, little or no study has been conducted on the evaluation of the mechanical and thermal properties of thermally reinforced nanocomposites.

In this study, nanoindentation method was used to study the load-displacement curve, nanohardness and elastic modulus of the synthesized NCs. Similarly, the thermal stability of the NCs was determined using TGA. Based on the results of the nanoindentation study and thermal characterizations, it was observed that the synthesised hybrid nanocomposites were mechanically and thermally enhanced compared to the neat recycled polystyrene materials. This was attributed to the inclusion of nanoparticles within the polymer matrix. Moreover, the morphology and compositions were also studied via SEM and EDX respectively; crystallinity and chemical bonding via XRD and FTIR respectively; and the homogenous dispersion of nanoparticles within the polymer matrix, the particle size diameters and the shapes of the NCs were all examined via TEM.

3.3. The Published Articles

The complete forms of all the published articles as emerged in the various journals and those under considerations are described in the consequent part with no modification. The questionnaires **(Appendices A and B)** used in this study have been placed at the end of the document immediately after the recommendation.

Paper 3: Recycling attitudes and behaviours towards municipal solid waste management at the University of Johannesburg, South Africa

(sent for publication in The Journal of Solid Waste Technology and Management)

Abstract

Rapid generation of municipal solid waste has become an issue of global concern. This is due to continuous population growth, changes in consumption pattern etc. To worsen the situation, members of public are not aware of the significant damages caused on public health and the environment by their indiscreetly activities. Hence, this paper aims to evaluate the attitudes and behaviour of staff and students at the University of Johannesburg towards waste management. To achieve this aim, a structured questionnaire was formulated and administered to a random sample of students and staff at the University of Johannesburg campuses. The statistical analysis of the data produced evidence of relationships between the data, and in addition, the variables obtained from the survey and the analysis allowed for the development of a logistic model prediction for the assessment of behavioural attitudinal pattern. The logistic model presented a positive correlation between the probability "yes" and median score of attribute responses towards willingness to support recycling. In terms of the reliability of the data collected, this was confirmed using Cronbach's alpha with a major significant α level between 0.72-0.93. The living condition of the respondents showed a significant relationship [p value of 5.95E-3 and 9.4E-6 ($p<0.05$)].

Keywords— Attitudes, logistic model prediction, municipal solid waste, sustainable solid waste management, University of Johannesburg, South Africa

1. Introduction

One of the major issues confronting municipalities globally is the problem of acute generation of municipal solid waste (MSW) (Addaney & Oppong, 2015). Studies have shown that MSW generation is directly linked to the living standard of people and the rate at which rural dwellers migrate to urban centres (Bandara et al., 2007; Bello, 2018; Liu et al., 2019; Omran et al., 2009; Zia et al., 2017). MSW could be described as every material that the original generator does not want to keep any longer but excludes hazardous material, liquid waste and atmospheric emissions (Beliën et al., 2012). The increasing volumes of MSW generated and its improper means of disposal have continued to pose a negative threat on public health and the environment (Alam & Ahmade, 2013; Ally et al., 2014; Sankoh et al., 2013). Improper disposal of MSW occurs mostly when waste remains uncollected due to low service coverage in some cities and largely in rural areas in developing countries (DCs) (Modak et al., 2010). The uncollected MSW usually provides a breeding ground for insects and pests and these ultimately spread diseases to the overall population (Le Courtois, 2012). Many nations of the world including South Africa (SA) are currently facing challenges that emanate from the increased quantities of MSW generated and these issues may continue to aggravate if the current method of waste management (WM) which is purely disposal of waste (e.g. plastic waste etc.) to landfills continues (Khatib, 2011).

Moreover, to assuage this issue, one of the options remaining is for low-income countries (LCs) to introduce a sustainable solid waste management (SSWM) plan through recycling of MSW (Elagroudy et al., 2016). This program will be appropriate for addressing issues associated with waste generation. However, its success is dependent on many factors, among which is the degree of awareness created for members of public. Public awareness/education campaign is crucial, in order to get the support of the public. The starting point would be appropriate with the students from Higher Institutions of Learnings (HIL) who we, believed would be having influence over their families and would by all means educate them on the need to support a SSWM plan (Khatib, 2011). Afterwards, the entire households within localities, suburbs or cities could then be engaged or a national survey could be carried out involving all stake holders for proper participation of the public in the implementation of a SSWM plan (Ong et al., 2019).

Hence, this study becomes very crucial as point of reference to enlighten the public on the need for proper WM and the need to support the SSWM plan or to act as a vehicle to convey the message on the need for a sustainable future to all municipalities and stakeholders in the developing nations. Thus, the students of the University of Johannesburg (UJ), Johannesburg, South Africa have been chosen to kick-start the campaign towards participation in SSWM for a sustainable future in Africa and globally. So far, there has been little or no study that has evaluated the perception, attitude and behaviour of people towards SSWM using students of Higher Institution of Learnings (HILs) as a case study to provide information for the higher education institutes specifically in South Africa and the City of Johannesburg to shape a recycling scheme.

2. Summary of studies on behavioural attitude on public vis-à-vis waste management

Attitudinal precession could be a positive or negative impression concerning a thing (s). It controls people's behaviour, and oftentimes, human behavioural judgments are repeatedly dependent on attitudes whether it is wilfully or not (Begum et al., 2009). Herremans and Allwright (2000) established that public awareness campaign and positive attitude can bring about a result-oriented WM and recycling program and in due course, a SSWM goals would be achieved (Herremans & Allwright, 2000). Sessa et al. (2010) reported that the level of awareness of the public is very shallow since different classes of people have different perceptions about MSW generation and disposal, hence there is a need for the modification of awareness which will in the end leads to attitudinal and behavioural changes towards WM (Sessa et al., 2010). Seng et al. (2018) also demonstrated that the level of awareness of the respondents with regards to WM is insubstantial. They reported that the key factors to the knowledge of the people are attributed to their educational qualification, income level and knowledge on environmental matters. When awareness level is high, there will be attitudinal and behavioural changes and many issues associated with WM will be eradicated (Seng et al., 2018).

Presently, the level of awareness of the public is very shallow and this has been affecting the attitudes and behaviours of people towards recycling (Jayasubramanian et al., 2015). One of the most amazing facts is that several people are not aware of the detrimental impact of their activities on other humans and on the ecosystem. It has been reported that most of the problems connected with improper WM like water pollution, soil, land and air pollution together with other health related issues are caused by the conscious and unconscious activities of the public (Jayasubramanian et al., 2015). Besides, municipalities in LCs are not contributing enough in the areas of public enlightenment/awareness campaigns to educate people on proper WM. Similarly, there are little or no new ideas and policies in place to address all these issues (Jayasubramanian et al., 2015).

Babaei et al. (2015) in their study, interviewed over 2000 respondents using a structured questionnaire to assess their levels of awareness with regards to WM and the attitudes of the people towards achieving a SSWM objectives. It was observed that most of the households interviewed were not well-informed on WM matters. Also, many of the respondents do not have access to MSW infrastructure, hence this hampers their willingness to pay more for qualitative services. The study revealed that only about 35% of the total samples were willing to pay more for qualitative waste collection services (Babaei et al., 2015). Keramitsoglou and Tsagarakis (2013) submitted that members of the public are to be carried along throughout the implementation stages of a SSWM plan or recycling program for optimum output. In that study, more than 300 respondents living in a township were engaged and their opinions were sought in connection with the running of a recycling program and their willingness to make the recycling program a success. Some of the questions asked in the study include, the willingness of the residents to recycle MSW, the number of waste bins or bags that would be needed for them to be actively involved in the scheme. Similarly, they were asked the type of economic incentive that would be appropriate, the modalities of the source separation program and what their opinions were in regard to shared responsibility by all stakeholders (including, public, municipalities, government, non-governmental organisation, policy makers etc.). The whole idea of that study was to engage the public and involved them in the designing of a sustainable recycling program (Keramitsoglou & Tsagarakis, 2018; Keramitsoglou & Tsagarakis, 2013). Kulatunga et al. (2006) stated that the mutual responsibilities of all stakeholders are required for a successful recycling program (Kulatunga et al., 2006).

Feo and Gisi (2010) in their study, sought the opinion of the public with regards to separate collection of various components of MSW. It was gathered that people were not properly informed on environmental issues. This might be impacting negatively on the attitudes and ultimately on the behaviours of public towards WM. Although, many of the respondents were highly educated, but it was inferred that the high level of education does not essentially correlate with high level of environmental awareness since there was no significant disparities amongst graduates and illiterates. Hence, having a higher educational qualification may not automatically relate to a high propensity to supporting a recycling program or a SSWM plan. Therefore, it is important that municipalities begin to educate members of the public on issues relating to the environment via awareness campaign, print media, questionnaire survey, training of WM staffs etc. (De Feo & De Gisi, 2010). **Table 1** showed the review of findings on attitudes and behaviours vis-à-vis waste management that have been reported in literature.

Table 1: Review of findings on attitudes and behaviours vis-à-vis waste management

Themes of previous studies	Sources
Issues associated with MSW generation and management	Addaney & Oppong (2015), Alam & Ahmade (2013), Ally et al. (2014), Sankoh et al. (2013), Modak et al. (2010), Le Courtois (2012), Khatib (2011)
Correlation between MSW generation and standard of living	Omran et al. (2009), Bandara et al. (2007), Zia et al. (2017), Liu et al. (2019), Bello (2018)
Mitigation to challenges of acute MSW generation	Khatib (2011), Ong (2019), Elagroudy (2016)
Knowledge, attitudes and behaviours towards WM	Herremans & Allwright (2000), Sessa et al. (2010), Seng et al. (2018), Jayasubramanian et al. (2015), Babaei et al. (2015), Keramitsoglou & Tsagarakis (2013), Omran et al. (2009)
Designing recycling scheme by the public and public opinion	Kulatunga et al. (2006), Feo & Gisi (2010), Keramitsoglou & Tsagarakis (2018), Keramitsoglou & Tsagarakis (2013)
Research tools employed by investigators	Neuendorf (2002), Siniscalco & Auriat (2015), Cooper & Schindler (2008), Insights Innovation (2006), Snijkers et al. (2013), Minister of Industry (2010), Lawson & Montgomery (2006), Begum et al. (2009), Maydeu-Olivares &´Garcia-Forero (2010), Cherian & Jacob (2012), Peng et al. (2002)

3. Materials and Methods

3.1. Description of study area

South Africa is located on 30.5595° South and 22.9375° East coordinates on the Africa continent. Johannesburg otherwise known as the City of Johannesburg (CoJ) is in Gauteng Province (GP), one of the nine provinces in the Republic of South Africa (RSA). Johannesburg is on 26.2023° South and 28.0436° East coordinates on the map of South Africa (Ayeleru et al., 2018). CoJ is the biggest city in RSA and it is considered as the financial hub or financial nerve centre of South Africa. Her contribution to the Gross Domestic Product (GDP) and employment rate is the highest in the nation, these indices serve as the main reason that attract people to CoJ (AyeleruNtuli et al., 2016a; City of Johannesburg, 2009). Johannesburg is at a height of 1,753 m and its current population is over ~6 million which is approximately around 10% of the total population of the RSA (AyeleruOkonta et al., 2016; GeoDatos, 2019; World Population Review, 2019). The population of Johannesburg rises every hour with an addition of almost 5 people, and it has been projected that by mid-century, its population will reach 9.2 million (City of Johannesburg, 2018/19). The beautification of the city is founded on nature which gave the city the tagged largest man-made garden, 17 nature reserves and several city parks configured across the city (City of Johannesburg, 2012/16). The University of Johannesburg (UJ) is unlike many other institutions which will be sharing the name of a city but will be situated elsewhere, not necessarily within the same city where its name is derived; for the university is situated in the centre of city and it also serve as one of the facets of CoJ (Ayeleru et al., 2017). The University was founded in 2005 due to the amalgamation that occur amongst the following Universities; Rand Afrikaans University (RAU), the Technikon Witwatersrand (TWR), the Soweto vista campus and East Rand campuses of Vista University (University of Johannesburg, 2011, 2012). UJ currently operates four campuses across the CoJ and these campuses are situated in Auckland Park Kingsway (APK) (main campus), Auckland Park Bunting (APB), Doornfontein campus (DFC) and Soweto campus (SWC). The UJ is an international and a Pan-Africa university with staff and students drawn from over 50 national from different Africa countries and other part of the world (Ayeleru et al., 2017).

3.2. Design, study setting and timeline

The study samples were the students and staff of the University of Johannesburg (UJ), South Africa. The sample size was evaluated depended on the total population of 50,000 students of the UJ. The confidence level and margin of error for this study were 95% and 1.87%. The CheckMarket Sample Size Calculator which is accessible on the internet was employed to evaluate the margin of error. A total of 4000 questionnaires were administered via both the paper-based and online Google form survey platform and the total number of respondents who took part in the survey were 2591. The first section of the questionnaire centred on the background information (gender, age, department/program of study, living condition and nationality); the second section concentrated on the recycling behavioural attitudes of staff and students of the UJ with questions like; (Are you residing at any of the UJ residences or off-campus accommodations?; What is the name of the UJ residence where you are residing?; Are there waste collection bins in your residences?; What issues do you normally experience with respect to your waste collection services?; Do you know where your collected waste is finally disposed?; Have you heard about recycling?; Are you currently separating wastes into different components?; Are there UJ employees who clean your rooms and residences?; Are there students who leave papers, plastic bottles etc. around on your campus?; Have you heard or seen people openly burning wastes on your campus?; Are there waste collection bins at different locations on your campus?; Which of the days of the week is waste collected on your campus?; Which waste management agency does UJ uses?; Which environmental problems do you experience on your campus?; Are there businesses at your residences? and finally, what is your average monthly spending?). Moreover, the Likert rating scale (1 – strongly disagree; 2 – disagree; 3 – neutral; 4 – agree; 5 – strongly agree) was employed at the latter part of the second section of the survey in which the following questions (recycling helps to conserve the environment; recycling reduces the amount of waste that goes to landfill; disposing of waste in a landfill harms the environment; recycling can be an alternative source of revenue in the CoJ; complete diversion of waste from landfill is an essential step to resource recovery; source separation of waste can lead to a sustainable city; dumping of waste to landfill sites contributes to climate change and proper handling of waste has both social and economic benefits) were asked. The third section of the survey delved into the factors that are encouraging willingness to support recycling (such as attitude; subjective norm; perceived behavioural control; perceived moral obligation; knowledge and inconvenience). The third section also consider the general information on recycling and employed Likert scale to probe whether waste reduction and reuse play important role in reducing environmental impact.

Moreover, the first stage of the study was conducted in all the four campuses of the UJ and lasted for almost the whole period of first Semester (January to May) in the 2018 academic year. The second stage of the survey was carried out in all the campuses but lasted from February to March 2020. The objective of the study was to evaluate the behavioural attitude of the students and staff of the UJ towards sustainable solid waste management (SSWM) proposition in the CoJ. This study employed the survey method to gather information from the students and staff of the UJ. The survey method was chosen in preference to other methods like content analysis because of its capacity to measure human attitudes and opinions. The content analysis is a research method used to analyse words or texts and to draw up a conclusion on the investigation. Researchers also used this method to carefully examine human interactions and to analyse characters on television (TV), films and novels (Neuendorf, 2002). Researchers often used closed questions, open-ended questions and contingency questions to generate reliable data from the respondents (Siniscalco & Auriat, 2015).

3.3. Background of municipal solid waste generation at the UJ and in City of Johannesburg

The UJ comprises of 29 student residences plus the four campuses which are the main sources of the generated MSW (Ayeleru et al., 2017). The bulk of these wastes are non-biodegradable while the biodegradable wastes are mostly from the Students' Centre (Cafeterias) located in each of the four campuses across the City of Johannesburg (CoJ) and some from the student residences. Currently, the UJ is having a WM system in place where all the generated MSWs are collected from the campuses bins and student residences and are moved to the transfer stations (TSs) where they are later transported to the landfill sites (LSs) within the CoJ. At the TSs, some recyclables are sometimes separated from other wastes, but the recycling rates is generally very low since the greater part of the generated MSW is sent to the landfills. Besides, there are no records on the amount of wastes generated at the UJ and there is no information on the quantity of recyclables being collected. Similarly, in the CoJ, there are no updated records of the generated MSW and the recyclables that are collected (Ayeleru et al., 2018). Based on the foregoing, in 2016, an initiative/a proposition was made by the CoJ to establish a bio-digester in the city and the UJ was awarded the contract of formulating a feasibility study on the proposed biogas plant. The main goal of the proposed plant is to process the generated organic fraction of municipal solid waste (OFMSW) into fuel for the running of the City's Metro Buses. The whole idea is to redirect all the biodegradable wastes/ OFMSW emanating from different sources in the CoJ, ranging from the Johannesburg Fruit and Vegetable Market (Joburg Market), residential areas, malls, markets, university campuses and residences, schools, offices etc. as feedstocks to the plant. One major drawback of the proposed plant is that it can only process the wet wastes while the non-biodegradable wastes are ending up at the landfills. In addition, the CoJ is currently having only four functional landfill sites (LSs) and all of them are having limited capacities before they will be closed down (AyeleruNtuli et al., 2016b). Similarly, the amount of generated waste is doubling owing to rapid influx of economic migrants to the CoJ and the recycling program is still at an infancy. Hence, the need for behavioural attitudinal changes amongst staff and students and even the general public become very crucial and this can be best achieved via waste education campaign using questionnaire survey (Sebola et al., 2014). **Figure 1** showed the position of South Africa, Johannesburg and the University of Johannesburg on the Africa continent alongside the four campuses of UJ designated as (a-d).

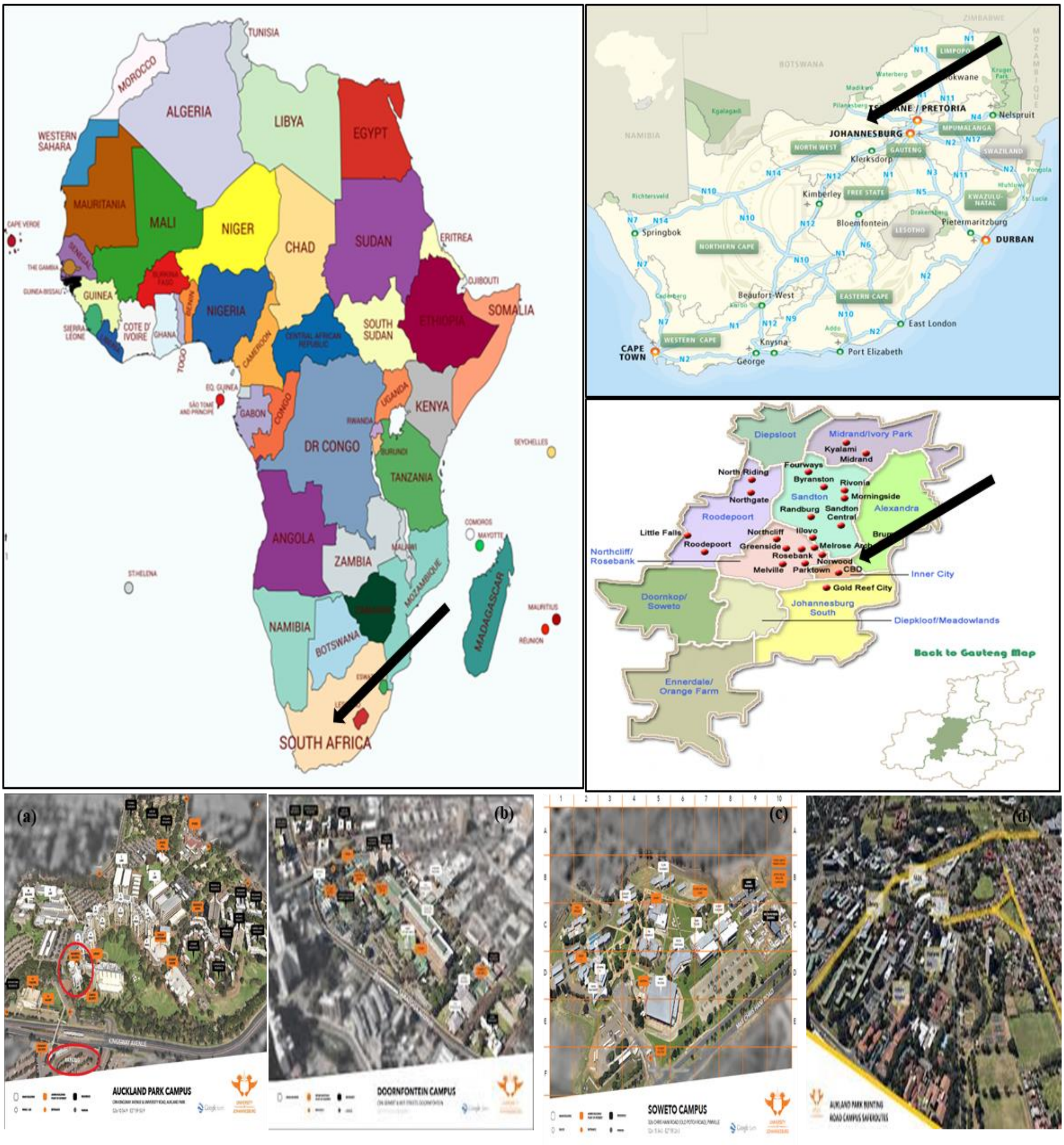


Figure 1: Map of Africa showing the position of South Africa, Johannesburg and locations of University of Johannesburg within the Johannesburg Central Business District (CBD)

3.4. Ethics Approval

Ethics approval was sought from the Ethics committee of the Faculty of Engineering and the Built Environment of the University of Johannesburg and it was granted before the commencement of the study.

3.5. *Primary Data Collection and Analysis (Qualitative*)

Qualitative method of research measures the behaviour of consumer, knowledge and opinions. The main aim of this is to provide answers to questions like, how much, how often, how many, when, who and what; when a data collection instrument known as questionnaire is utilized. Most oftentimes, a questionnaire is the instrument that is employed in research. Developing a questionnaire is partly science and partly art (Cooper & Schindler, 2008). A structured questionnaire was administered to students and staff at the UJ. The number of questionnaires distributed was 4000, the total number of respondents was 2591 where 2541 responses were from the students and only 50 responses were from the staff. The questionnaires were administered to the students by the first author alongside 4 other co-authors and 22 undergraduate diploma students. About 20% of the questionnaires were completed in the first month of the exercise. The identities of the respondents were not requested. The survey questionnaires were administered to the students and staff at different locations which include, the libraries in all the four campuses, offices, lecture halls and theatres, student cafeteria, and at the student residences. The exercises were carried out three times daily throughout the period of the exercise.

3.6. Research Design & Methodology

The main aim of this research methodology was to evaluate the behavioural attitude of students towards recycling of MSW which will ultimately pave the way for a SSWM proposition in the CoJ. To achieve the research objectives, information was gathered from students of different study levels in the various programs offered at the UJ through qualitative statistical research methods. Qualitative data was gathered by means of a structured questionnaire survey conducted on the selected students and staff for this study. Secondary information was gathered through articles, reports, books, published and unpublished materials and from the internet. A survey is a method of research used to gather data from a group of people with the aid of methodized questionnaire. A survey involves selection of population, pre-testing instruments, analysis of data etc. (Insights Innovation, 2006). Surveys are mostly used to gather information from a small group of a population and the output is frequently generalized to the overall population (Snijkers et al., 2013). A survey is a method in which information is gathered in an organised way with the aid of well-defined concepts in order to provide a useful summary. A survey is usually employed when there is a need for information and the need sometimes arises within a particular organization or outside (Minister of Industry, 2010).

3.7. Logistic regression model

This is applied predominantly to output variable that is binary, but it can be altered to process nominal or ordinal data (Lawson & Montgomery, 2006). Considering binary variables, the regression model is given as follows;

$$y_i = \mathbf{x}_i'\boldsymbol{\beta} + \varepsilon_i$$

(Population of 2019)

Where $\mathbf{x}_i' = [1, x_{i1}, x_{i2}, \dots, x_{ik}], \boldsymbol{\beta} = [\beta_0, \beta_1, \beta_2, \dots, \beta_k]$ and the response, y_i,can only take on the values of 0 or 1. The response is assumed to be a Bernoulli random variable with a probability distribution;

$$y_i = 1, \quad \boldsymbol{P}(y_i = 1) = \pi_i$$

$$y_i = 0, \quad \boldsymbol{P}(y_i = 0) = 1 - \pi_i$$

As $E(\varepsilon_i) = 0$, the expected value of the response is;

$$E(y_i) = \mathbf{x}_\mathbf{i}'\boldsymbol{\beta} = 1\ (\pi_i) + 0\ (1 - \pi_i) = \pi_i$$

(Population of 2019)

The expected value of the response function, $E(y_i) = \mathbf{x}_i'\boldsymbol{\beta}$, is the probability that the response takes the value of 1.

One of the issues with this regression model is that the error term only accepts two values.

$$\varepsilon_i = \begin{cases} 1 - \mathbf{x}_i'\boldsymbol{\beta} & \text{when } y = 1 \\ -\mathbf{x}_i'\boldsymbol{\beta} & \text{when } y = 0 \end{cases}$$

Consequently, the errors in this model cannot be generally distributed and therefore the error variance is not usually constant. However, for real world practical examples, we can assume mean of the errors are approximately zero.

$$\begin{aligned} \sigma^2 &= E\{y_i - E(y_i)\}^2 \\ &= (1 - \pi_i)^2\pi_i + (0 - \pi_i)^2(1 - \pi_i) \\ &= \pi_i(1 - \pi_i) \end{aligned} \tag{3}$$

Which is the same as:

$$\sigma^2 = E(y_i)[1 - E(y_i)]$$

$$0 \le E(y_i) = \pi_i \le 1$$

$$E(y) = \pi_i = \frac{\mathrm{e}^{\mathrm{g(x)}}}{1+\mathrm{e}^{\mathrm{g(x)}}} = \frac{1}{1+\mathrm{e}^{-\mathrm{g(x)}}} \tag{4}$$

$$\mathrm{g}(\mathbf{x}) = \ln\frac{\pi}{1-\pi} \tag{5}$$

$$f_i(y_i) = \pi_i^{y_i}(1 - \pi_i)^{1-y_i}\text{for } i = 1,2,\dots,n \tag{6}$$

$$L(y_1, y_2, \dots, y_n, \boldsymbol{\beta}) = \prod_{i=1}^{n} f_i(y_i) = \prod_{i=1}^{n} \pi_i^{y_i}(1-\pi_i)^{1-y_i} \quad (7)$$

$$\ln L(y_1, y_2, \dots, y_n, \boldsymbol{\beta}) = \sum_{i=1}^{n} \left[y_i \ln\left(\frac{\pi_i}{1-\pi_i}\right)\right] + \sum_{i=1}^{n} \ln(1-\pi_i) \quad (8)$$

$$\ln L(\mathbf{y}, \boldsymbol{\beta}) = \sum_{i=1}^{n} y_i \pi_i + \sum_{i=1}^{n} n_i \ln(1-\pi_i) - \sum_{i=1}^{n} y_i \ln(1-\pi_i)$$

$$\hat{\mathbf{g}}(\mathbf{x}) = \mathbf{x}'\boldsymbol{\beta} \quad (10)$$

$$\hat{y} = \frac{1}{1+\exp(\mathbf{x}'\boldsymbol{\beta})} = \pi_i \quad (11)$$

4. Results and Discussions

4.1. Demographic results

The key question which this paper addresses is whether someone is “willing to support recycling” with nominal responses as “Yes/No”. In lead up to the logistic model described in the section, this response variable has been statistically tested against demographic data from the study. The method used is a chi-squared test since the variables are categorical. The relationships are analysed against the province where the student was raised and the stage at which the student is studying, undergraduate or postgraduate. Moreover, the gender ratio of respondents is fairly evenly split, while the age groups of the students are relatively of a younger audience between 16 and 25 years old which is the expected sample of university students.

In the analysis comparing the provinces where the student was raised, there is not enough statistical evidence at a 5% level of significance to identify if there was a dependent relationship and thus statistically, we concluded that the variables are independent. This means there is no relationship and their willingness to support does not depend on their provinces of origin. The statistical evidence yielded a Chi-Square value of $\chi^2 = 8.55$, dof = 8 and p-value= 0.3818.

The investigation against the demographic variable of level of study presented a relationship regarding their willingness to support. The results produced statistical evidence at 5% level of significance to conclude there is a dependent relationship between their decision to support and whether they are Undergraduate/Postgraduate student. The following statistics were a Chi-Square value of 4.41, dof=1, p-value = 0.035. Moreover, in the residual analysis and investigating why dependence was being exhibited, it was influenced by the Postgraduate students and they are lower than initially expected number of them “not willing to support”. This was the only unexpected statistic from this particular analysis and the reason is uncertain. Another interesting statistical result which is notable pertains to the collection of bins and their willingness to support. The statistical evidence ($\chi^2 = 53.272$, df = 1, p-value = 0) concludes it is statistically dependent that willingness to support is related to whether the bins are collected infrequently or no issue. The influence on willingness is in fact higher if there is “No Issue” of bins rather than “infrequent collection”. This suggests that trying to do infrequent collection is worse off than doing nothing and not providing bins. This could be contingent on psychological factors of being offered the choice and nothing at all. It has been apparent from the final analysis that there is an independent relationship between the variables. **Table 2** and **Table 3** showed the demographic information (Gender, Age, Living condition and Program) and (Country of Origin and Provinces in South Africa) respectively for all the respondents where the “blank” indicated that there are no response or questions were not answered by the respondents. **Table 4 (a) and (b)** showed willing to support recycling with various demographic variables using Chi-square test.

Table 2: Demographic information (Gender, Age, Living condition and Program)

Variable	Percentage
Gender	
Male	48%
Female	51%
Other	1%
Age	
16 - 21 years	51%
22 - 25 years	39%
26 - 30 years	8%
30 years and above	2%
(blank)	< 1%
Living condition	
Residing alone	36%
With a parent or family member	14%
With a partner with children	1%
With a partner without children	2%
With roommate (s)/sharing	46%
(blank)	1%
Program	
Exchanged Student	0%
Postgraduate International Student	3%
Postgraduate South African Student	12%
Undergraduate (International Student)	8%
Undergraduate South African Student	75%
(blank)	2%

Table 3: Demographic information (Country of Origin and Provinces in South Africa)

Variable	Percentage
Country of origin	
International Student	11%
South African	88%
(blank)	1%
Province (South Africans only)	
Eastern Cape	4%
Free State	3%
Gauteng	39%
KwaZulu-Natal	8%
Limpopo	17%
Mpumalanga	9%
North West	6%
Northern Cape	2%
Western Cape	1%
(blank)	12%

Table 4: Correlation of willing to support recycling with various demographic variables

The relationship between the attitudes and general behavior of the studied population towards willingness to support recycling is presented below

a) Attitudes against various demographics and willingness to study.

The correlation was studied at 5% significance level and the chi-square value, together with degree of freedom is presented below

Attitude, Demographics and Willingness to Support Recycling (significance level for p value was estimated at 5%)

Attitude

Gender	Willing to Support Recycling			Total	p value	x2(Chi-square)	df
	Yes	Neutral	No				
Male	91	0	3	**94**	0.407863	0.023975246	2
Female	102	2	3	**107**			
Total	**193**	**2**	**6**	**201**			

Attitude

Living Condition	Willing to Support Recycling			Total			
	Yes	Neutral	No		p value	x2(Chi-square)	df
Residing alone	48	1	0	**49**	0.000595	1.506596371	10
With a parent or family member	32	0	0	**32**			
With a partner with children	6	0	1	**7**			
With a partner without children	2	0	0	**2**			
With roommate (s)/sharing	107	0	0	**107**			
Undisclosed	4	0	0	**4**			

Total	**199**	**1**	**1**	**201**			

	Attitude						
Age	Willing to Support Recycling			Total			
	Yes	Neutral	No		p value	x2(Chi-square)	df
16-21	110	2	3	**115**	0.829821	1.054392807	8
22-25	42	0	2	**44**			
26-30	16	0	0	**16**			
>30	10	0	1	**11**			
Undisclosed	15	0	0	**15**			
Total	**193**	**2**	**6**	**201**			

In terms of the attitude of the studied populace towards recycling, the location of the people contributed significantly to the positive attitude of the people towards willingness to support recycling. The p value was significant with a value <0.05.

b) General Attitude of the studied population, against demographics and willingness to support recycle

General Behavior, Demographics and Willingness to Support Recycling (significance level for p value was estimated at 5%)

Attitude

Gender	Willing to Support Recycling			Total	p value	x2(Chi-square)	df
	Yes	Neutral	No				
Male	117	5	2	**124**	0.72791	0.712530043	2
Female	118	5	4	**127**			
Total	**235**	**10**	**6**	**251**			

General Behavior

Living Condition	Willing to Support Recycling			Total			
	Yes	Neutral	No		p value	x2(Chi-square)	df
Residing alone	56	2	0	**58**	9.4E-06	2.334502627	10
With a parent or family member	39	0	0	**39**			
With a partner with children	22	1	0	**23**			
With a partner without children	12	0	0	**12**			
With roommate (s)/sharing	112	0	0	**112**			
Undisclosed	6	0	1	**7**			
Total	**247**	**3**	**1**	**251**			

General Behavior

Age	Willing to Support Recycling			Total			
	Yes	Neutral	No		p value	x2(Chi-square)	df
16-21	105	8	3	**116**	0.65559	3.22107513	8
22-25	43	1	2	**46**			

26-30	20	0	0	**20**
>30	51	2	1	**54**
Undisclosed	14	0	1	**15**
Total	**233**	**11**	**7**	**251**

Status	Willing to Support Recycling			Total	p value	x2(Chi-square)	df
	Yes	Neutral	No				
Student	185	10	6	**201**	0.58513	1.926113984	2
Staff	49	1	1	**51**			
Total	**469**	**21**	**13**	**503**			

In terms of the attitude of the studied populace towards recycling, the location of the people contributed significantly to the positive attitude of the people towards willingness to support recycling. The p value was significant with a value <0.05.

4.2. Recycling behavioural attitude towards waste management

This current study examined students' and staff attitudes towards recycling of MSW at the UJ. From the data gathered via the questionnaire survey administered to a cross-section of students and a random number of staff at different time of the day and at various locations within the four campuses of the UJ, it was observed that involvement in recycling of MSW is more dependent on the level of awareness created to the public. Thus, constant education and provision of WM infrastructure to the general populace could be the right step in the right direction as this might eventually lead to positive attitude and behavioural changes towards SSWM (Omran et al., 2009). Results obtained from this study showed that about 70% do not have the idea of where their generated wastes are taken to after collection, 72% are not currently separating their wastes from source, 75% did not respond to the question; how do you separate wastes? Moreover, 77% are willing to support recycling of MSW (**Table S1**). It was therefore concluded that the bulk of the students are not well-informed on environmental matters. However, the majority of them indicated interest in recycling program and SSWM and they are willing to support the initiatives. **Table S1** showed the summary of students' behavioural attitudes towards recycling at the University of Johannesburg (UJ), South Africa.

4.3. Logistic model prediction

The subject of waste management (WM) has become a multifaceted concept that requires data from different fields, hence this informed the use of logistic prediction model (**Figure 2**) in this study to evaluate the perception of students towards WM and their willingness to support recycling (Yes/No) (Cherian & Jacob, 2012). Logistic regression allows us to analyse a binary variable (Yes/No) associated with a probability of the outcome - *Yes*. The regression model is mathematically related to the common approach of linear regression **(Table 5)**, but since a binary outcome is being model then we employ the logit link function which belongs to the family of a binomial response variable (Sperandei, 2014). This fundamental mathematical linkage function called the logit function is the natural logarithm of an odds ratio and the most common example is a logit function which is based from a 2 × 2 contingency table (Peng et al., 2002). This allows us to accommodate suitable input variables, which are categorical variables. This prediction can be carried out using least squares regression, where 0/1 variable is treated like the target. Thus, a "Yes" is defined as the occurrence of the outcome coded as 1. It is then assumed that the probability of success for a given set of values for the predictor variables is given by Equation 13,

$$\mathrm{p|x} = \beta_0 + \beta_1 \mathrm{x}_1 + \cdots + \beta_k \mathrm{x}_k \qquad (12)$$

The responses of the questions given the sample were ordinal variables attributed to a scale from 1 to 5. The specific values on the scale from 1 to 5 describes their opinion to the questions through the natural increasing scale ("1= Strongly Disagree", "2 = Disagree", "3= Neutral", "4 = Agree", "5 = Strongly Agree"). The following model which best described the relationship and possessed statistical significance is a model using the median of the predictors of the responses for each person. This means Equation (13) becomes simplified to:

$$p \mid x = \beta_0 + \beta_1 \bar{x} \qquad (13)$$

By using the median as the predictor variable to describe this situation and has values ranged from 1 to 5. The coefficients of the model above were examined for statistical significance in R and there was not enough statistical evidence at 5% level of significance to support the overall model when the constant coefficient is non-zero and since it would not be meaningful here. Thus, we deduce that b_0 is not zero and re-run the model without the coefficient. However, the coefficient estimates for β_i presents strong evidence and a strong relationship between the variable, *Median Score of the Attributes* **(Figure 3)** in the Survey through a logit function, the p-values are all basically zero with the largest equal to 0.028101.

The comparison between the coefficients in the values for the median are listed in the output. On a scale from the inputs from 1 to 5, there is only a small difference between estimates other than when the Median score = 1.5 and the error is just above 1. In the analysis, the results produced are interpreted by increasing the median score of the scale by one unit then the log odds of agreeing with the statement differs, however, overall are likely to support. The model below includes the confidence interval for the logistic model. It is noticeable that the lower the median score then the larger the error and thus the confidence interval. However, if there are at the high end of scale (towards 4 and above), then the error is small and in the interval is smaller as well. In terms of probability, we can covert the log odds to probability of agreeing and below is a logistic graph of the model for different values for the medians **(Table 6)**. This is more relatable when looking at the comparisons. For example, if someone has an average median score of 4 then the probability of agreeing with the statement of support is 78.48%. It was noticed from the model that the probability on average for a score of 1 is 76.92%. This presents an informative observation regarding the chance of someone willing to support, which is that overall students (even if they disagree with the statements) are willing to support are in the majority. **Figure 4** shows the average score of respondents who are willing to support recycling.

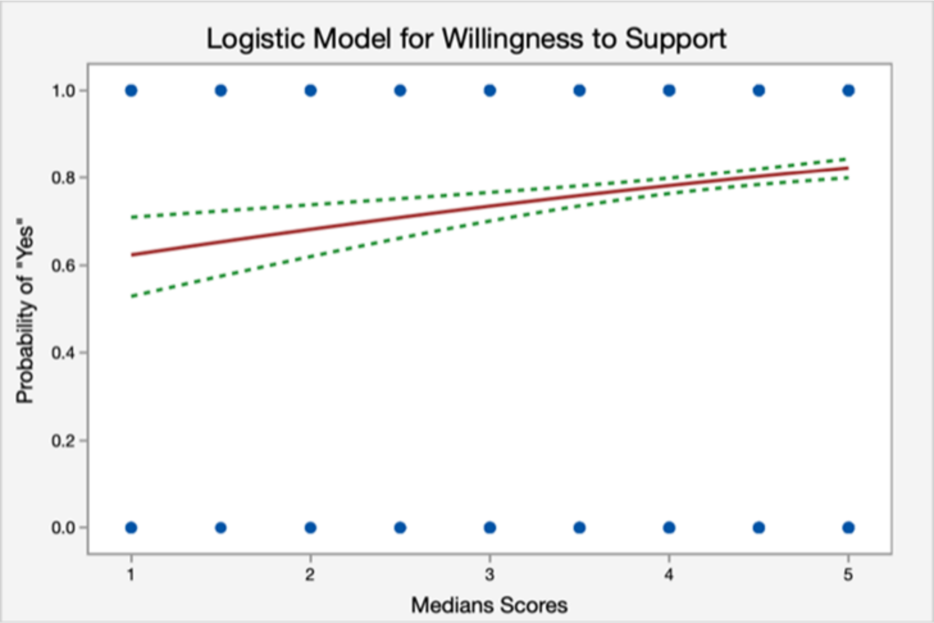
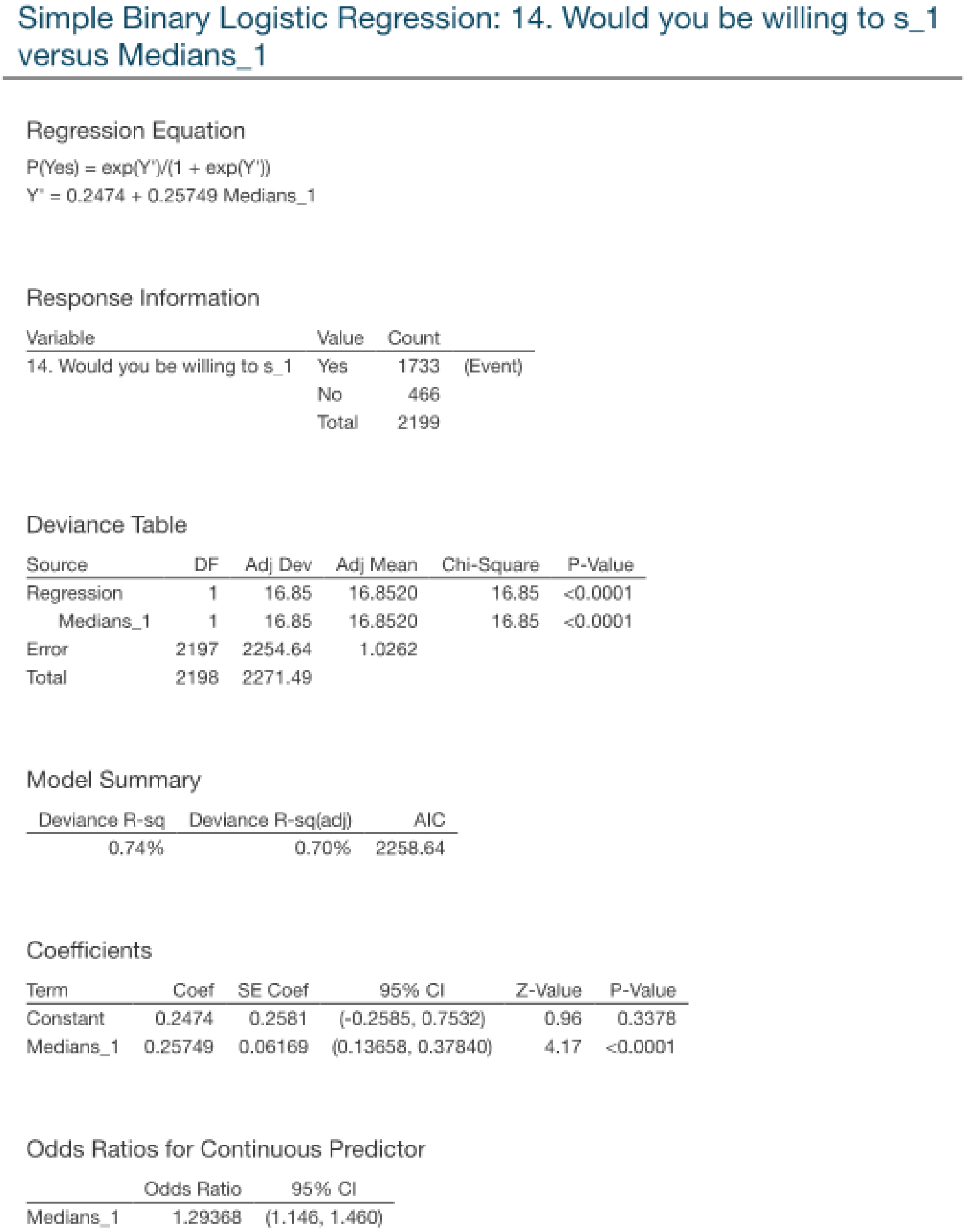


Figure 2: Logistic model prediction for people who are willing to support recycling

Table 5: Simple Binary Logistic Regression: Yi versus Xi



Simple Binary Logistic Regression: 14. Would you be willing to s_1 versus Medians_1

Regression Equation

P(Yes) = exp(Y')/(1 + exp(Y'))
Y' = 0.2474 + 0.25749 Medians_1

Response Information

Variable	Value	Count	
14. Would you be willing to s_1	Yes	1733	(Event)
	No	466	
	Total	2199	

Deviance Table

Source	DF	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	1	16.85	16.8520	16.85	<0.0001
Medians_1	1	16.85	16.8520	16.85	<0.0001
Error	2197	2254.64	1.0262		
Total	2198	2271.49			

Model Summary

Deviance R-sq	Deviance R-sq(adj)	AIC
0.74%	0.70%	2258.64

Coefficients

Term	Coef	SE Coef	95% CI	Z-Value	P-Value
Constant	0.2474	0.2581	(-0.2585, 0.7532)	0.96	0.3378
Medians_1	0.25749	0.06169	(0.13658, 0.37840)	4.17	<0.0001

Odds Ratios for Continuous Predictor

	Odds Ratio	95% CI
Medians_1	1.29368	(1.146, 1.460)

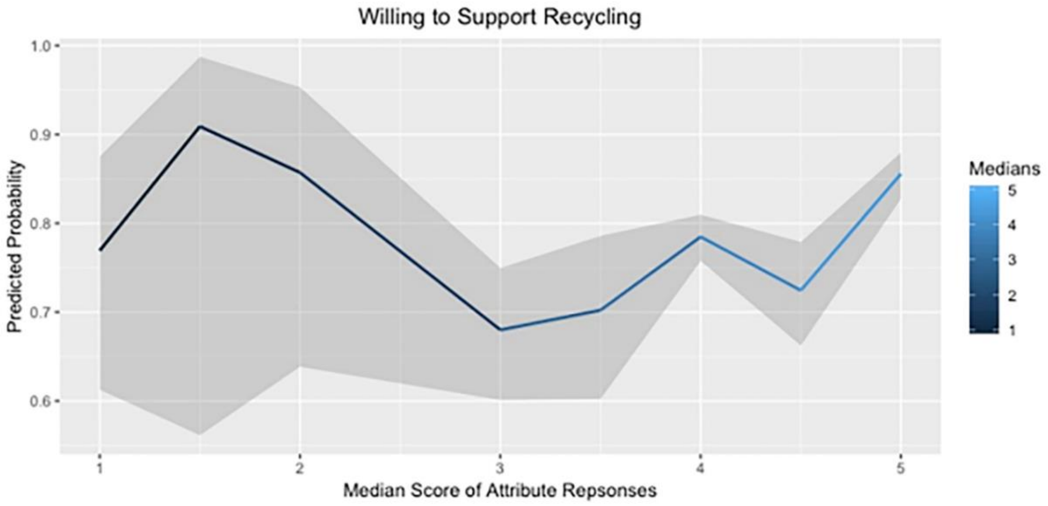
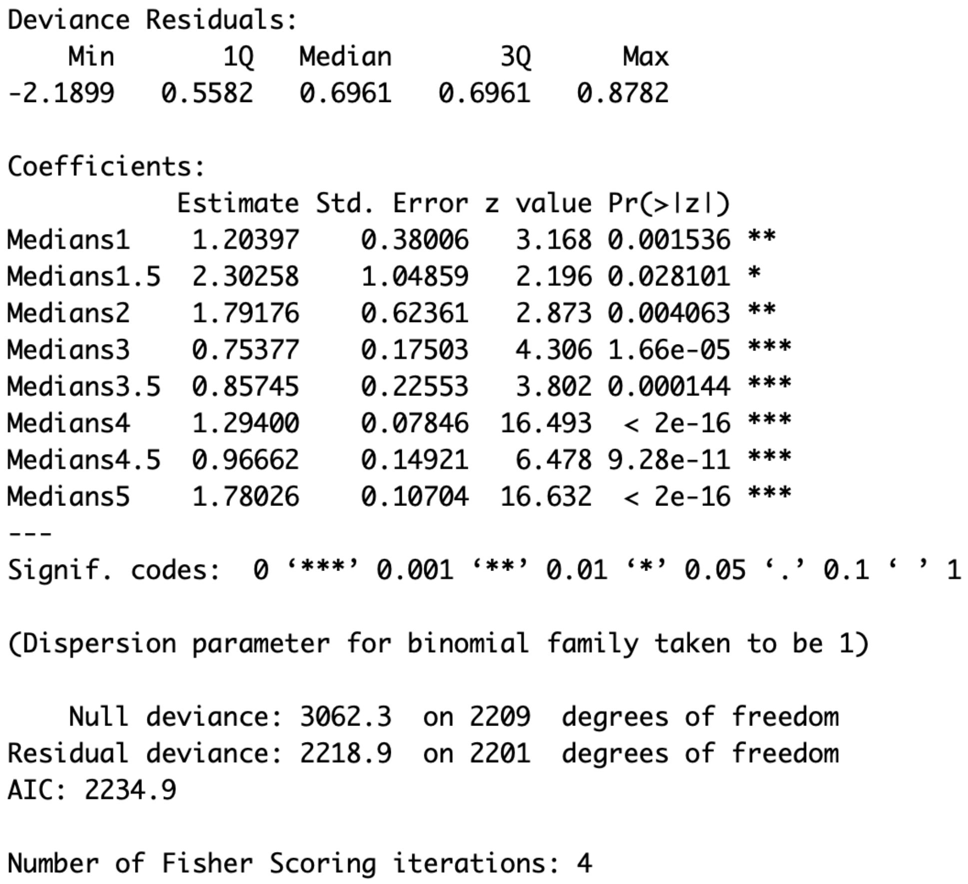


Figure 3: Median score of attribute responses

Table 6: Comparison between the coefficients in the values for the media


```
Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.1899   0.5582   0.6961   0.6961   0.8782

Coefficients:
           Estimate Std. Error z value Pr(>|z|)
Medians1    1.20397    0.38006   3.168 0.001536 **
Medians1.5  2.30258    1.04859   2.196 0.028101 *
Medians2    1.79176    0.62361   2.873 0.004063 **
Medians3    0.75377    0.17503   4.306 1.66e-05 ***
Medians3.5  0.85745    0.22553   3.802 0.000144 ***
Medians4    1.29400    0.07846  16.493  < 2e-16 ***
Medians4.5  0.96662    0.14921   6.478 9.28e-11 ***
Medians5    1.78026    0.10704  16.632  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 3062.3  on 2209  degrees of freedom
Residual deviance: 2218.9  on 2201  degrees of freedom
AIC: 2234.9

Number of Fisher Scoring iterations: 4
```

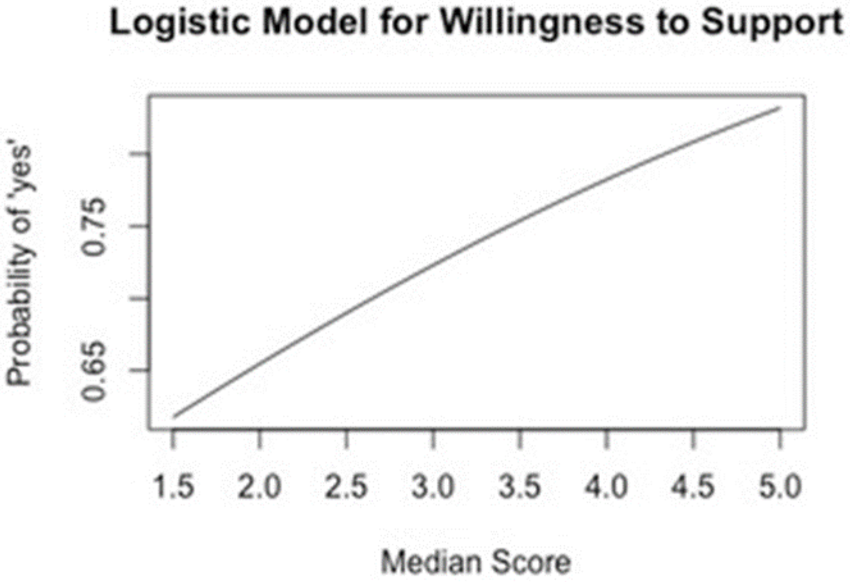


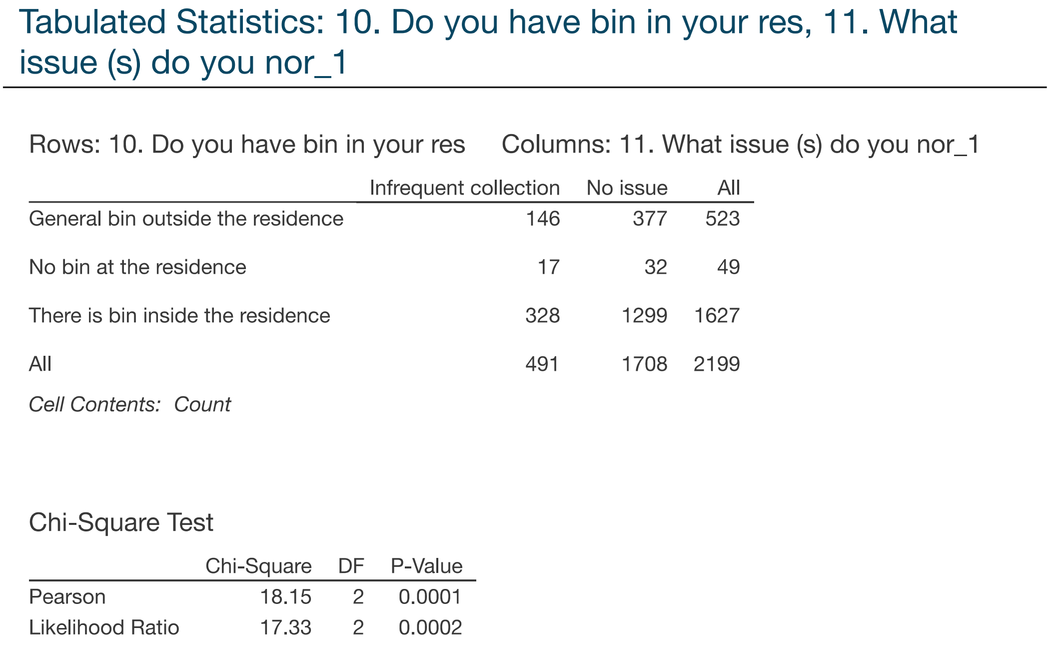
Figure 4: Average score on logistic model for people who are willing to support recycling

This model includes an intercept and statistically this needs to be removed because there is enough statistical evidence at 5% level of significance to set it to zero. In R, we produce a zero intercept model which makes statistically sense. We break the medians into increments of half and conduct a logistic regression model. **Table 7 (a)** and **(b)** showed the results of comparison of models.

Table 7: Comparison of models

Notice the relationship between “What issue do you normally experience with respect to your waste collection services” and “Do you have bins in your residence” statistically implies that these two variables are dependent.

Table 7 (a)



Tabulated Statistics: 10. Do you have bin in your res, 11. What issue (s) do you nor_1

Rows: 10. Do you have bin in your res Columns: 11. What issue (s) do you nor_1

	Infrequent collection	No issue	All
General bin outside the residence	146	377	523
No bin at the residence	17	32	49
There is bin inside the residence	328	1299	1627
All	491	1708	2199

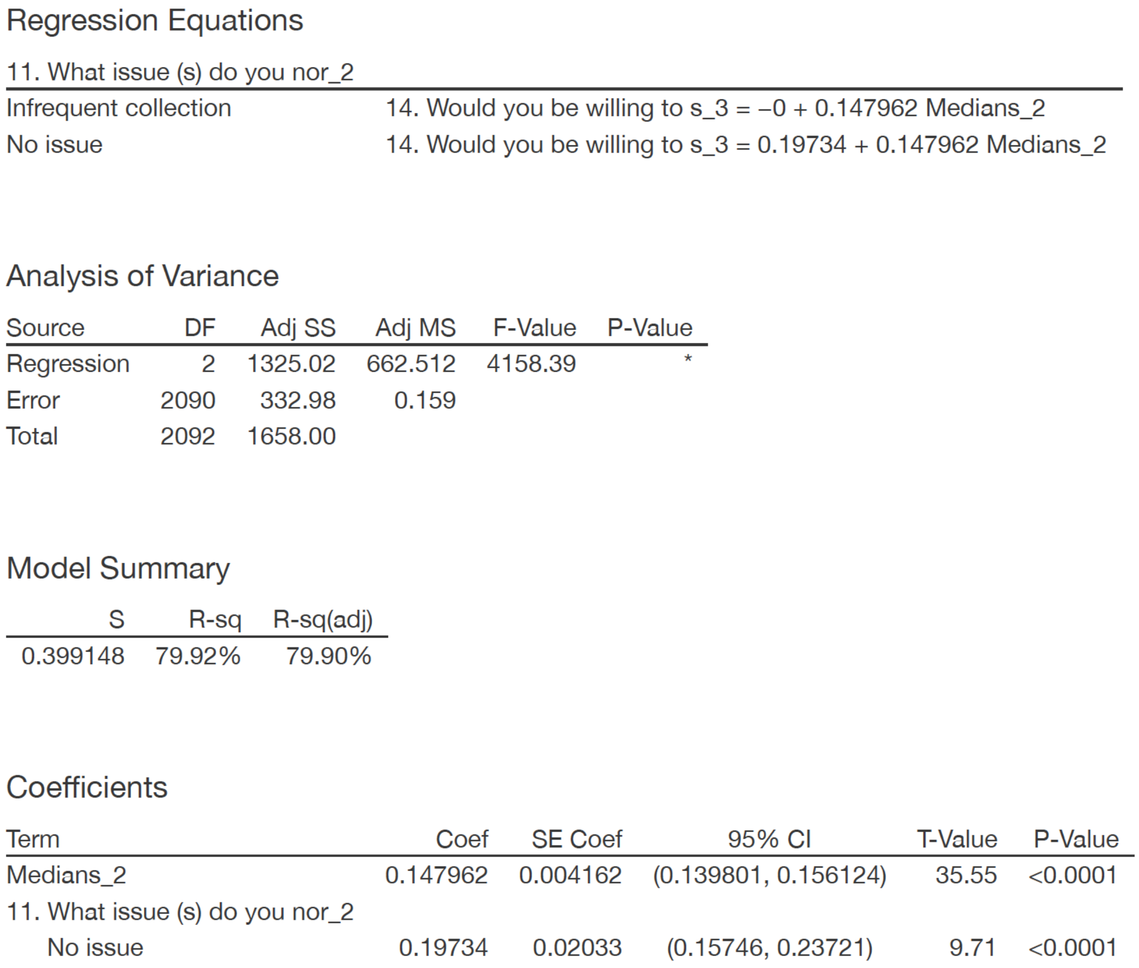
Cell Contents: Count

Chi-Square Test

	Chi-Square	DF	P-Value
Pearson	18.15	2	0.0001
Likelihood Ratio	17.33	2	0.0002

In the next model, we decide to test the variable of “what issue method” and use it in the regression model with the medians. Note that the data needed to be cleaned and this is why there is a difference in the number of observations. The model indicates there is a relationship when the categorical variable of what issue type is included.

Table 7 (b)



Regression Equations

11. What issue (s) do you nor_2	
Infrequent collection	14. Would you be willing to s_3 = −0 + 0.147962 Medians_2
No issue	14. Would you be willing to s_3 = 0.19734 + 0.147962 Medians_2

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	1325.02	662.512	4158.39	*
Error	2090	332.98	0.159		
Total	2092	1658.00			

Model Summary

S	R-sq	R-sq(adj)
0.399148	79.92%	79.90%

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value
Medians_2	0.147962	0.004162	(0.139801, 0.156124)	35.55	<0.0001
11. What issue (s) do you nor_2					
No issue	0.19734	0.02033	(0.15746, 0.23721)	9.71	<0.0001

4.4. Reliability Statistics Cronbach’s alpha

It measures the reliability or internal consistency of a set of scale. α level greater than 0.5 implies that there’s internal consistency amongst the set of items (questions) under each construct. For the set of constructs that were considered during the evaluation of the study, the construct consists of those summarised below. **Table 8** presented the summary of the factors influencing recycling.

Table 8: Factors influencing recycling amongst students

Construct	Items	α
Attitude	6	0.440468499
Subjective Norm	5	0.832259278
Perceived Behavioral Control	5	0.74708276
Perceived Moral Obligation	6	0.868295345
Knowledge	5	0.722398055
Inconvenience	5	0.824742399
General Information on Recycling	9	0.934001148

4.5. Comparison between data from the University of Johannesburg survey with data from other universities globally

Though, comparing behavioural attitudinal pattern with respect to recycling of MSW at the UJ on a global level would be a great idea, however the performance of recycling at various institutions of learning varies from nations to nations and from continent to continents. Hence, comparing such data may be a bit challenging since the environment is not the same. The most common information to all the studies includes, the gender, age group and possibly, the factors influencing the willingness to recycle. Data obtained from this survey have been compared with data from other surveys globally and these have been presented in **Table 9**. It was observed that the data from this study were within the scope of other past studies which is typically of an international university. Data for the 'attitude' is a bit low compared to other studies because the responses received from the survey were not evenly distributed.

Table 9: Comparison between data from the University of Johannesburg survey with data from other universities globally

Research and year	**Philippsen (2015)**	**Ahmad et al. (2016)**	**Balkaya & Bilgin (2019**	**Bashir et al. (2020)**	**This study**
Survey			**Percent**		
Gender					
Male	43	73	57.4	41.9	48
Female	57	27	42.6	58.1	51
Other	–	–	–	–	1
Age			**Percent**		
15-25	84.21	70	94.8	55.4	90
26-35	13.16	30	4.7	44.6	8
36-45	2.63	–	0.2	–	2
> 46	–	–	0.2	–	–
Means of managing wastes			**Percent**		
Recyclable waste collection	–	–	–	91.4	26
Using recycling bins	–	–	–	–	11
Reuse	–	–	–	–	–
Food waste separate collection	–	–	–	14.3	14
Information on recycling	–	–	–	–	31
Willingness to support recycling	–	–	–	–	77
Factors influencing willing to recycle			**Average**		
Attitude	0.634	0.52	–	–	0.441
Subjective norm	0.735	0.51	–	–	0.832
Perceived behavioural control	0.897	–	–	–	0.747
Perceived moral obligation	0.903	0.75	–	–	0.868

Knowledge	0.556	0.772	–	–	0.722
Inconvenience	0.935	0.84	–	–	0.825
General information on recycling	–	–	–	–	0.934

5. Limitations of the Study

One of the most critical limitation of the present study is its restriction to a higher institution of learning (HIL) (UJ). Moreover, every study no matter how it is structured has its own limitation. This study has several features that may limit the generalisation of its findings. Some of the challenges encountered were in the administering of questionnaires and the collection of data owing to the attitudes of some of the respondents. Some of the respondents (students) were not willing to complete the questionnaires (about 5%), some collected it and did not return it (10%), some questionnaires were incomplete (5%), some answers did not make sense (6%) and the handwritings of some of the respondents were not clear on some of the questionnaires (7%). Moreover, it was very difficult getting the staff members participation in the survey since the majority of them were given different excuses such as busy schedules and some did not return the paper-based questionnaires while others did not response to the online questionnaire. Hence, this basically impact on the number of responses received which made it to be around 2% of the total respondents.

Conclusion

In this study, the perception of the students of the UJ and their willingness to support MSW recycling initiatives and the proposition in the City of Johannesburg and South Africa at large were evaluated via analysing the relationships in the data and building a logistic model to predict chances of support. The logistic model prediction showed notable outcomes. It was gathered that the level of awareness of the students with respect to WM and recycling is very low since over two-third of the respondents do not know the extent of the damaging impacts of their activities on public health and the environment. It was observed that most of the respondents (about 80%) are willing to participate in a recycling program. Nevertheless, the willingness of the respondents might not essentially turn into high recycling rates. Based on the outcome of this study it is recommended;

- that policy makers (e.g. municipal authorities, non-governmental organisations, provincial government and national/federal government) should pay adequate attentions to the yearnings of the masses by educating them and providing them with modern WM infrastructure.
- that policy makers should reinvigorate the perception of the public towards WM by way of dissemination of information to schools and colleges, and in the end leading to redoubling involvement in recycling.
- that municipalities continue to offer trainings and awareness campaign to WM workers as new WM plans are being designed and unfolded.

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*Dlamini; Tatenda Gutsa; Tembuso Dlamini; Yonela Madlebe; Mbasa Ntsaluba and David Nzodi w*ho assisted in the administering of the questionnaires.

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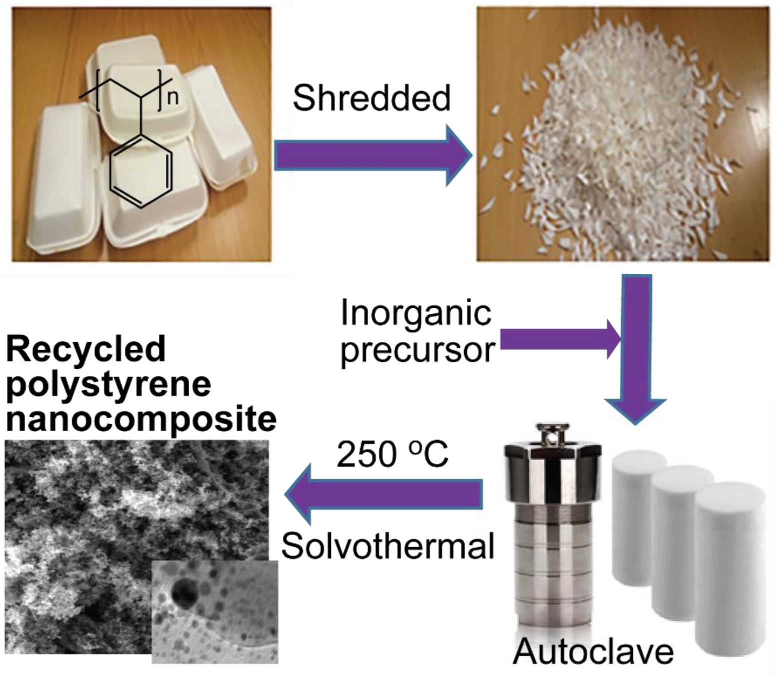
Paper 4: Novel green route towards synthesis of recycled polystyrene-based nanocomposites via solvothermal technique

(Submitted for publication in Pollution Research)

GRAPHICAL ABSTRACT



Highlights

- Recycled polystyrene was used to develop Nanocomposites.
- XRD results revealed that rPS were crystallised after addition of ZnO and Ag particles.
- XPS and FTIR results showed successful incorporation of Zn and Ag elements in rPS matrix.

Abstract

Hybrid organic/inorganic nanocomposites (NCs) comprised of recycled polystyrene (rPS) and; zirconium nitrate (Zr $(NO_3)_4$), zinc (IV) carbonate ($ZnCO_3$) and silver nitrate ($AgNO_3$) as precursors were prepared using solvothermal method. Effects of the inclusion of nanoparticles on the properties of rPS were studied. The rPS (control) and the hybridized NCs comprising of rPS/$Zr(NO_3)_4$, rPS/$ZnCO_3$ and rPS/$AgNO_3$ were characterized by different techniques. X-ray photoelectron spectroscopy (XPS) was used to determine the elemental compositions; X-ray diffraction (XRD) showed the crystallinity. Fourier transform-infrared (FTIR) revealed the interface affinity and chemical structures. Scanning electron microscopy (SEM) and Transmission electron microscopy (TEM) exhibited the morphology, particle size and the homogenous dispersion of nanoparticles within the rPS matrix. Thermogravimetric analysis (TGA) presented the enhancement in thermal stability. Differential scanning calorimetry (DSC) exhibited slight increment in glass transition temperatures by 17 ℃ for ZrO_2 NC, 19 ℃ for ZnO NC and 6 ℃ for Ag NC. Brunauer-Emmett-Teller (BET) revealed slightly higher surface areas compared to rPS. Nuclear magnetic resonance (NMR) showed there was no chemical shift in the rPS and the neat polymers. Gel permeation chromatography (GPC) presented the molecular weight (Mw) distribution of rPS and the neat polymers dispersed in organic solvent. It was therefore demonstrated that the properties of the hybridized nanocomposites were significantly enhanced due to the inclusion of nanoparticles in the rPS matrix.

KEYWORDS: Nanocomposite; Solvothermal technique; Nanoparticle; Inorganic metallic precursors; Plastic polymer material

1. Introduction

Plastic polymer material (PPM) has become an essential part of the daily lives of people in the 21st century (Koç, 2013. This is because of its durability, low-cost, lightweight, portability and ability to reduce energy consumption (Foerster, 2017). Recent studies have shown that about 8 billion plastic bags are consumed in South Africa every year (McLellan & Aquarium, 2014). The increased usage of plastics has led to the rapid generation of plastic wastes (PWs) in the municipal solid waste (MSW) streams in many developing countries (DCs) including South Africa (Koç, 2013). These PWs are non-biodegradable materials with no economic value that can be derived from them especially when they are deposited to the landfill sites (LSs). Owing to their proliferation, PWs now litter the streets in many major cities in the DCs since they are often blown away by wind from the disposal sites causing harms to wild and marine animals (Ayeleru, Okonta, & Ntuli, 2016). A research has shown that over a million marine animals are killed by PWs (Butterworth, Clegg, & Bass, 2012). Marine animals often mistaken plastic debris for food thereby ingesting them and, in many cases, when the fragments pass through their guts; it settled in their digestive tracts and this often leads to starvation (Allsopp, Walters, Santillo, & Johnston, 2006). The fast rate of PWs generation goes hand-in-hand with its impacts on the environment (Almeida & Marques, 2016). While, there are several factors that are widely accepted as the major contributing factors to the massive increased generation of PWs all over the world, the most common ones are the rapid population growth, industrialization; economic growth and high standard of living (Patni, Shah, Agarwal, & Singhal, 2013).

In many DCs including South Africa, as the population increases so also is the quantity of wastes generated, the bulk of which is PW. For instance, in 2017, the population was approximately 57 million according to Statistics South Africa (STATS SA) (STATS SA, 2017), the total amount of MSW generated was over ~40 million tons, the amount of waste plastic was about ~2 million tons and the total amount of recycled waste was less than ~5 million tons In 2014, the total quantity of PW generated in South Africa was around 1.5 million tons, the amount recycled was 0.3 million tons and the quantity deposited to the landfill sites (LSs) was about 1.2 million tons (Motsoai, 2015). In South Africa, the most common methods of PW management are by incineration and landfilling, which are not environmentally friendly since carbon dioxide (CO_2) is usually released to the atmosphere through the processes and thus contributing to global warming (Quartey, Tosefa, Danquah, & Obrsalova, 2015). Although, there are several other methods of PWs recycling which include; primary recycling, mechanical recycling, chemical recycling and energy recovery that have been used but when these methods are utilized, the structure of PPM are usually degraded leaving poor thermal properties. Therefore, for the thermal properties of PPM to be enhanced while also mitigating environmental issues caused by PWs, one of the option left is in the development of nanocomposites (NCs) from the wastes (Zare, 2015). NCs are materials with improved properties such as thermal stability, chemical reagent resistant etc. compared to single nanomaterial. They are formed from the combination or matrix of different metals resulting in new materials with size range of 1-100 nm (Akpan, Shen, Wetzel, & Friedrich, 2019; Chae & Kim, 2005).

NCs are materials of superior value to industries and they have been prepared through various routes during the last decades (Oliveira & Machado, 2013). Some of the methods used thus far include; the sol-gel, melt blending, in-situ polymerization, solution blending, direct compounding and melt intercalation (Khan, Hamadneh, & Khan, 2016). Sol-gel method involves mild reaction conditions and building up of materials from molecular precursors leading to materials and properties variations. The product obtained from this method is mostly films or colloid. This process involves the simple wet chemical reaction which depends on hydrolysis and condensation that forms sol and when it aged, an integrated network known as gel is formed. This method has gained attention in the research community, but it has some limitation, for example; high temperature that can decompose polymer matrix and the NCs formed could aggregate the processing condition that may be unfavourable (Karak, 2019). The melt blending method is used to prepare polymer NCs from thermoplastics polymeric matrix. In this case, the polymer is subjected to heat and it is added to a known quantity of intercalated clay using an extruder. This method takes place in an inert environment (Rane, Kanny, Abitha, & Thomas, 2018). The disadvantages of this method are in the poor dispersion of the polymer into the polymer matrix, particularly in higher filler loadings owing to the increased viscosity and buckling of the polymer due to compelling shear forces that may not be favourable application as a conductive polymer NCs (Verma & Goh, 2019). In the in-situ polymerization method, NCs are prepared by mixing solution containing monomer. This is because the monomers with low molecular weight easily leaks in between the strata regions where the inflating of polymer occurs. The mixture obtained is polymerized either using radiation or heat. The monomer then polymerized between interlayers thereby forming exfoliated or intercalated NCs. Some studies have shown that covalent linkages take place between the polymer matrix and the NCs formed. The disadvantage of this method is the high temperature required which can cause polymer to decompose (Paszkiewicz & Szymczyk, 2019). Solution blending is a commonly used method for NCs preparation. In this method, polymers and fillers are blended together in good solvents. This method involves mixing of polymer solutions and fillers dispersed in appropriate solvents. The product sample is isolated from the solvents and the final product obtained is the NCs. The demerits of this method are the difficulty in getting good solvents and where the solvents are available, the difficulty involved in isolating the solvents from the final product could be a major challenge (Ravichandran, Praseetha, Arun, & Gobalakrishnan, 2018). The direct compounding is a cost-effective method used by most researchers to synthesis NCs and it can be easily scale-up. In this case, nanomaterials and polymers are produced differently using varied methods before they are blended to form NCs. The method is limited owing to the performance of nanoparticles within the polymer matrix since some nanomaterials can form aggregates which makes homogenous dispersion of materials in the matrix to be extremely difficult to achieve (Ucankus, Ercan, Uzunoglu, & Culha, 2018). The melt-intercalation is also one of the preferred methods used by researchers since the use of solvents is not required and the process can be achieved through the same processing conditions used for higher polymers. However, this method requires the use of heat which in many occasions, may be higher than the softening point of polymers. Hence, this could also be a major drawback to this method (Filippi, Mameli, Marazzato, & Magagnini, 2007).

Thus far, Zirconium (IV) oxide (ZrO_2) NCs, Zinc oxide (ZnO) NCs and Silver (Ag) NCs have been prepared through some of the various routes discussed earlier. The ZrO_2 NC is an essential substance with good natural colour, high strength, transformation toughness, high chemical stability, excellent corrosion; chemical and microbial resistances; and a wide band gap p-type semiconductor showing copious oxygen openings on its outside (Hwangbo & Lee, 2019). This material has been prepared through sol/gel (Suciu, Gagea, Hoffmann, & Mocean, 2006), vapour phase (Moravec, Smolík, Keskinen, Mäkelä, & Levdansky, 2007), spray pyrolysis (Zhang, Mulholland, & Messing, 1996), pyrolysis (Keskinen et al., 2004), hydrolysis (Keskinen et al., 2004) etc.

Moreover, ZnO NC is an expansive band gap semiconductor that possesses excessive thermal, chemical and mechanical stability. It is having an energy gap of 3.37 eV and excellent physical and chemical properties (Shahine et al., 2019). Due to its distinctive properties like the catalytic, electrical, optoelectronic and photochemical, it has found applications in many fields and these have made it popular in recent times (Uikey & Vishwakarma, 2016). ZnO NC has wide range of usages in semiconductors, solar cells, catalysts, pigments, electronics, nanogenerators, gas sensors, biosensors, pharmaceuticals, sunscreens, food flavours, colourants and electrical materials; and photocatalysts (Awwad, Albiss, & Ahmad, 2014). ZnO is also used to enhance the tribological properties of the polymeric matrices when the thermal conductivity of polymeric materials changes (Bochkov et al., 2015). ZnO NC has been synthesized through some of the routes reviewed earlier (Bochkov et al., 2015). Furthermore, silver (Ag) NC has been accepted in the field of nanotechnology because of its physical, chemical, optical, catalytic, biological, electrical, thermal and antimicrobial properties (Richter et al., 2017). Ag NC has a wide range of applications in household products such as plastics, food packaging, soaps and food because of its antimicrobial properties (Pulit-Prociak & Banach, 2016). Owing to the different properties of Ag NCs, they are now applied as fillers in polymer matrix (Vodnik, Božanić, Džunuzović, Vukoje, & Nedeljković, 2012). Some Ag nanoparticles (NPs) have very high plasmon resonance absorption and when they are combined with polymers to produce NCs, they enhance the optical performance of the polymers (Lee & Jun, 2019). Ag NCs have been considered as good NCs since they are conductive and chemically stable (Rajan et al., 2016). Ag NCs are innocuous to man, animals and the environment particularly when they are at slight intensities compared to other substances. Ag NCs have also been prepared through some of the methods described above (Raza et al., 2016). All of the approaches that have been utilized are either limited by one or more factors which include, complicated procedures, high reaction temperature, long reaction time and high cost of production which make them unfit for commercial scale application (Keiteb, Saion, Zakaria, & Soltani, 2016).

Therefore, it is expected that the present study would be helpful in addressing the issue of the structure of PPM which often degrade when plastic is poorly managed and thereby leading to poor thermal. To the best of our knowledge, little or no study on the development of NCs using recycled polystyrene and inorganic metallic precursors via solvothermal method to evaluate the thermal stability of recycled polymers blended with nanoparticles has been carried out till date.

2. Experimental

2.1. Materials

Zirconium nitrate ($Zr(NO_3)_4$, ≥ 99% purity) was purchased from British Drug House (BDH). Zinc carbonate ($ZnCO_3$, ≥ 53% Zn basis), silver nitrate ($AgNO_3$, ≥ 99% assay) and xylene (≥ 98.5%, ACS reagent), lithium chloride (LiCl, ≥ 99%), tetrahydrofuran (THF, anhydrous, ≥ 99.9%), deuterated chloroform ($CDCl_3$, 99.96 atom % D, containing 0.03 % (v/v) TMS) and *N*,*N*-dimethylformamide (DMF, anhydrous, 99.8%) were purchased from Sigma Aldrich. All chemicals were used as received. Ultrapure water was obtained from a Milli-Q system. Waste polystyrene was collected from the University of Johannesburg recycling facility (Johannesburg, South Africa), and was washed with water and shredded using an OminiBlend laboratory blender (I-2ltr Pro, TM767). A solvothermal stainless steel? autoclave reactor (Labotec; 250 mL) with a Teflon bomb was purchased from Protea Laboratory Solution (Pty) Ltd, Johannesburg, South Africa.

2.2. NC Sample preparation

The NCs were prepared via in situ nanoparticle formation using a solvothermal method in accordance to our previous study (Ayeleru et al., 2020). Shredded polystyrene (5.00 g) was dissolved in xylene (50 mL) with sonication for 20 min at room temperature. The solution was transferred into a Teflon bomb (250 mL) and placed inside a solvothermal autoclave reactor at 250 °C for 3 h. After cooling to ambient temperature, the rPS was isolated as a brown powder (93%). This sample served as a control. For the synthesis of the NCs, polystyrene (5.00 g) was dissolved in xylene (50 mL), sonicated for 20 min and (5.00 g) inorganic precursors (comprising $Zr(NO_3)_4$, $ZnCO_3$ and $AgNO_3$ respectively) were added.

Each mixture was sonicated for 20 min and transferred into a Teflon bomb and placed into the autoclave reactor at 250 °C for 3 h. Subsequently, NCs were isolated from the bomb as powders and offered ZrO_2, ZnO and Ag NCs.

The organic soluble fraction of the NCs was determined by adding the NCs (ZrO_2 NC: 305.5 mg; ZnO NC: 306.5 mg; Ag NC: 179.1 mg) to THF (10 mL), followed by sonication (30 min) and centrifugation (600 rpm, 2 h). The supernatant was removed and used for further analysis, whereas the insoluble components were dried under vacuum (0.1 mbar, 12 h) to calculate the insoluble and soluble fractions of the NCs (ZrO_2, ZnO, Ag NC were 84.8, 85.1 and 86.8 wt%, respectively). The NC powders were also melt processed into discs for testing; the NC powder (1 g) was placed in a stainless-steel cylindrical mould and placed in an oven at 150 °C for 1 h, and then compressed (10 tonnes) into a disc using a hydraulic press.

2.3. Characterization of NCs physical properties

X-ray photoelectron spectroscopy (XPS) was performed on a SPECS SAGE spectrometer equipped with a non-monochromated X-ray Mg K_α (hν = 1253.6 eV) source operated at 10 kV and 20 mA. Samples were hydraulically compressed (10 tonnes) into discs for analysis. The analysis chamber was held at a pressure lower than 9×10^{-7} Pa during measurements. A survey spectrum was acquired over the binding energy range 0-1100 eV at a pass energy of 100 eV and a step size of 0.5 eV. High-resolution spectra were acquired with a pass energy of 20 eV and a step size of 0.1 eV. Quantification of atomic percentages were performed using CasaXPS software (version 2.3.14dev38), provided by the XPS manufacturer. CasaXPS software was also used to perform curve-fitting analysis on the high-resolution spectra. Charging effects of the samples during analyses were corrected using a value of 285.0 eV for the binding energy of the main C 1s component arising from neutral hydrocarbon (i.e. C-H/C-C). The line shape of the curves was assumed to be Gaussian–

Lorentzian with a 30% Lorentzian component and a Shirley-type background was used throughout the analysis. Within a single peak, Gaussian–Lorentzian mixing ratio, peak width for all components and peak position were constrained to maintain consistency and optimization for comparison between the samples.

X-ray diffraction (XRD) was conducted on a Rigaku D-MAX/IIA X-ray diffractometer (XRD) (Sweden) operating at 40 kV and 30 mA over a 2θ range from 0º to 100º at the scan speed of 0.50 deg./min. The NCs (ZrO_2, ZnO and Ag) were finely ground, homogenized and sieved employing ASTM standard sieves. Fourier transform infrared spectroscopy (FTIR) was conducted on a Thermo Scientific FTIR spectrophotometer (range 4000 cm^{-1} to 1000 cm^{-1}), using samples prepared as KBr discs.

Scanning electron microscopy (SEM) was performed on a VEGA3 TESCAN at 20 kV. Samples were mounted onto holders using double-sided carbon tape. The double-sided carbon tape was stuck on a glass slide and each of the samples was stuck to the carbon tape. The glass slide on top of each powder was pressed, shaken and the sample was loaded into SEM chamber. Transmission electron microscopy (TEM) was performed on a JEOL JEM-2100 at a voltage of 200 kV. The samples were prepared by adding a few drops of freshly prepared suspension of NCs in ethanol on to a carbon coated copper (Cu) grid allowing the solvent to evaporate. Dynamic light scattering (DLS) was conducted on Malvern Zetasizer Nano Z500 at 25 ºC. The NCs (50 mg) were added to THF (1.2 mL), sonicated for 30 min, and the insoluble component was removed via centrifugation (350 rpm, 15 min). The supernatant was diluted 1:10 in THF prior to DLS analysis.

Thermogravimetric analysis (TGA) was conducted on an Advanced Laboratory Solution SDT Q600 V8.3101. The NCs (5 mg) were characterized at a heating rate of 10 ºC/min and in an inert environment ranging between ambient temperature and 600 °C.

Differential scanning calorimetry (DSC) was performed on a Mettler Toledo DSC822 in a nitrogen environment using a heating rate of 10 °C/min from room temperature to 500 °C.

Brunauer–Emmett–Teller (Moon) surface analysis of the NC powder was conducted on a Micromeritics ASAP 2020.

Proton (1H) nuclear magnetic resonance (NMR) spectroscopy was performed on a Bruker Avance III 500 MHz operating at 500 MHz. The samples (5-6 mg) were dissolved in deuterated chloroform (0.6 mL) for analysis.

Gel permeation chromatography (GPC) was conducted on a Shimadzu liquid chromatography system (RID-20A RI detector, SPD-10A UV detector) fitted with three columns (GPC-804D, GPC-8025D, GPC-80MD) in series at 60 ºC using a conventional column calibration with polystyrene standards supplied by Polymer Standards Service (PSS). 0.05 M LiCl in DMF was used as the mobile phase at 1 mL/min. Samples were dissolved in the mobile phase at a concentration of 2-3 mg/mL, vortexed for 1 min, and passed through a syringe filter (PES membrane, 0.45 µm) prior to analysis. NMR spectra and GPC chromatograms are provided in the Supplementary Information (SI) (**Figure S1, Table S1 and Figure S2**).

3. Result and Discussions

Recycled polystyrene (rPS) nanocomposites (NCs) were prepared via a solvothermal process, where inorganic precursors ($ZnCO_3$, $Zr(NO_3)_4$ and $AgNO_3$) were individually mixed with solutions of polystyrene in a Teflon bomb and heated to 250 ºC for 3 h. Thus, ZrO_2, ZnO, and Ag NCs were isolated and obtained as powders. A control sample was also prepared through the same process using polystyrene solution only.

3.1 Chemical composition and structure

3.1.1 XPS

X-ray photoelectron spectroscopy (XPS) was used to determine the elemental composition of the NCs, especially the inorganic components. The rPS and NC powders were hydraulically pressed (10 tonnes) into discs. XPS of the rPS revealed the presence of a C1s peak consistent with a carbonaceous material (SI, **Figure S3**, **Table S2**), as well as some trace elements (4% O, 1% Si, 1% Cl and 0.8% Sn). The preliminary survey spectra of the NCs revealed predominantly the presence of carbon (85-96 %) and oxygen (3-9 %) for all the samples (SI, **Figure S4-6**). For the ZrO_2, ZnO and NCs, the elemental composition of Zn and Zr were found to be 2.6 and 0.2 %, respectively, whereas no Ag was detected in the Ag NC. The low levels of Zn, Zr and Ag detected in the NCs were believed to result from masking of the nanoparticle signal with polystyrene (Baer & Engelhard, 2010), and therefore, the inorganic component of the NCs was separated for further analysis by dissolving the soluble component in THF.

XPS analysis of the insoluble components, revealed the presence of Zn, Zr and Ag in the NCs (SI, **Figure S7-9**, **Table S3-5**). High-resolution XPS spectra of the inorganic component of the NCs indicated that Zn and Zr were present as oxides, whereas Ag was predominantly in its elemental form (**Figure 1**, **and SI, Table S6-8**). For the ZnO NC, the binding energies of the $Zn2p_{3/2}$ peak (1021 eV), along with deconvolution of the O1s peak, suggested that both stochiometric and non-stochiometric ZnO was present. For the ZrO_2 NC, peaks were observed for $Zr3d_{3/2}$ (182.7 eV), $Zr3d_{5/2}$ (185.1 eV) and O1s (530.4 eV), consistent with zirconia (ZnO_2). However, deconvolution of the O1s also revealed the presence of hydroxides and possibly water (532.1 and 533.5 eV), indicating that various zirconium oxides may be present. The Ag NC displayed a characteristic $Ag3d_{5/2}$ peak at a binding energy of

368.4 eV for elemental silver (Ag^0), as well as a peak at 369.6 eV consistent with Ag clusters (Galindo, Benito, Palacio, Cavaleiro, & Carvalho, 2013).

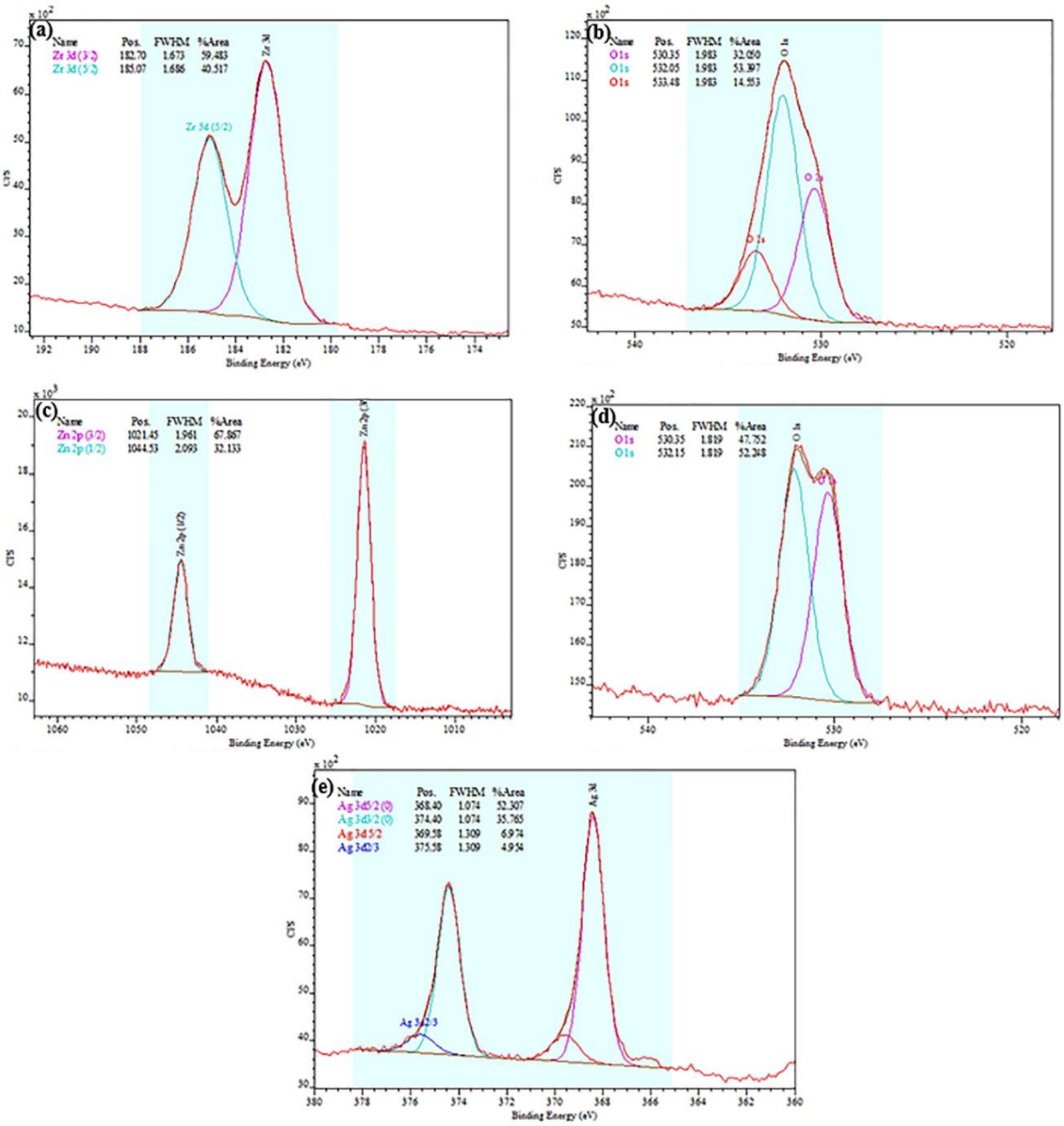


Figure 1: High-resolution deconvoluted XPS spectra for the (a) Zr3d and (b) O1s peaks in the ZrO_2 NC, (c) Zn2p and (d) O1s peaks in the ZnO NC, and (e) Ag3d peak in the Ag NC. Elemental composition determined from high-resolution XPS spectra are provided in the SI, Tables S6-8

3.1.2 FTIR

FTIR spectrophotometry of rPS and the NCs revealed peaks typically characteristic with that of polystyrene (**Figure 2**), including aromatic and aliphatic C-H stretches (3032 and 2933 cm^{-1}, respectively) and aromatic C=C stretches (1492 and 1600 cm^{-1}). For the ZrO_2 and Ag NCs, no distinct peaks were observed for the inorganic component. In comparison, the ZnO NC displayed two distinct peaks at 1394 and 3308 cm^{-1}, which are characteristic of C-H vibrations (Chae & Kim, 2005). Given that no variation in the polystyrene peaks were observed in the FTIR spectra of the NCs, it would suggest that the polystyrene is not chemically modified during the solvothermal process. Furthermore, the absence of characteristic peaks corresponding to the inorganic precursors $ZnCO_3$, $Zr(NO_3)_4$ and $AgNO_3$ supports the XRD results (SI, **Figure S11**).

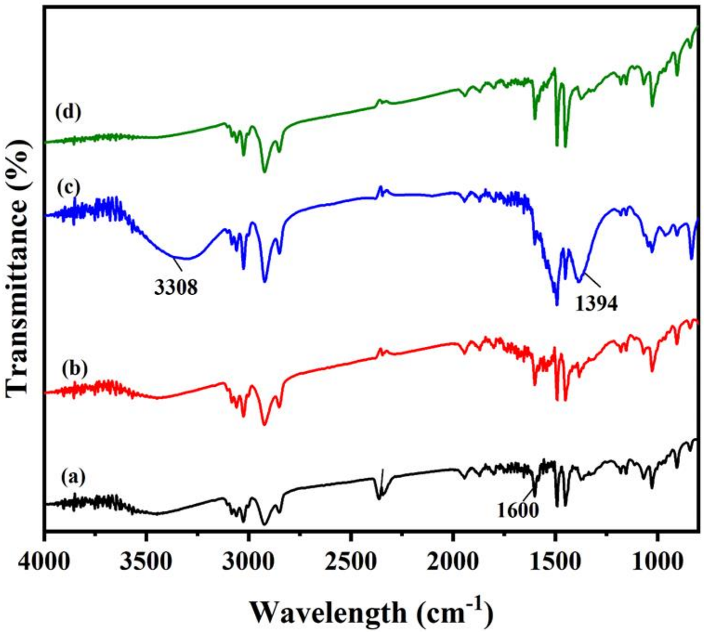


Figure 2: FTIR spectra of (a) rPS, and the (b) ZrO_2, (c) ZnO and (d) Ag NCs. All samples display characteristic polystyrene peaks with no significant peaks from the inorganic components with the exception of the ZrO_2 NC, which displays broad peaks consistent with the exception of the ZrO_2 NC, which displays broad peaks consistent with hydroxy groups.

3.2 Crystallization behaviour of NCs

3.2.1 XRD

The crystallinity of the rPS and the NCs were evaluated by XRD analysis (**Figure 3**). The XRD spectra of rPS revealed broad diffraction peaks at 2θ values of 10.1° and 18.7°, consistent with amorphous polystyrene (Niculăescu, Olar, Stefan, Todica, & Pop, 2018; Wankasi & Dikio, 2014). The XRD pattern of the ZnO NCs revealed a broad peak at 2θ value of 20° consistent with amorphous polystyrene and the sharp diffraction peaks in line with the wurtzite polycrystalline phase of ZnO (JCPDS card number 36-1451), and in agreement with ZnO nanoparticles prepared according to (Alwan et al., 2015; Mohan & Renjanadevi, 2016). In comparison, the XRD pattern for the ZrO_2 NCs (**Figure 3**) revealed two broad peaks that were not located over any of the lattice planes (~ 31° and 82°), indicating that the material is amorphous, and the peaks are likely due to a short-range collection of ZrO_2 bonds (Saligheh, Khajavi, Yazdanshenas, & Rashidi, 2016), although the broad peak at 31° has been reported to correspond to an amorphous phase of ZrO_2 having incipient crystallization (Alves et al., 2016). The XRD pattern of the Ag NCs (**Figure 3**) revealed peaks corresponding to the face-centred cubic crystal lattice for Ag (JCPDS card number 04-0783) as previously reported for Ag nanoparticles (Vijayan, Joseph, & Mathew, 2018), as well as a broad peak at 2θ values of 20° indicative of amorphous polystyrene. The XRD results in combination with the XPS results provide good evidence that the solvothermal process employed in this work generates NCs containing ZnO, ZrO_2 and Ag nanoparticles. Furthermore, the absence of characteristic diffraction peaks corresponding to the inorganic precursors $ZnCO_3$, $Zr(NO_3)_4$ and $AgNO_3$ imply that they are completely converted to their oxide or elemental forms (SI, **Figure S10**).

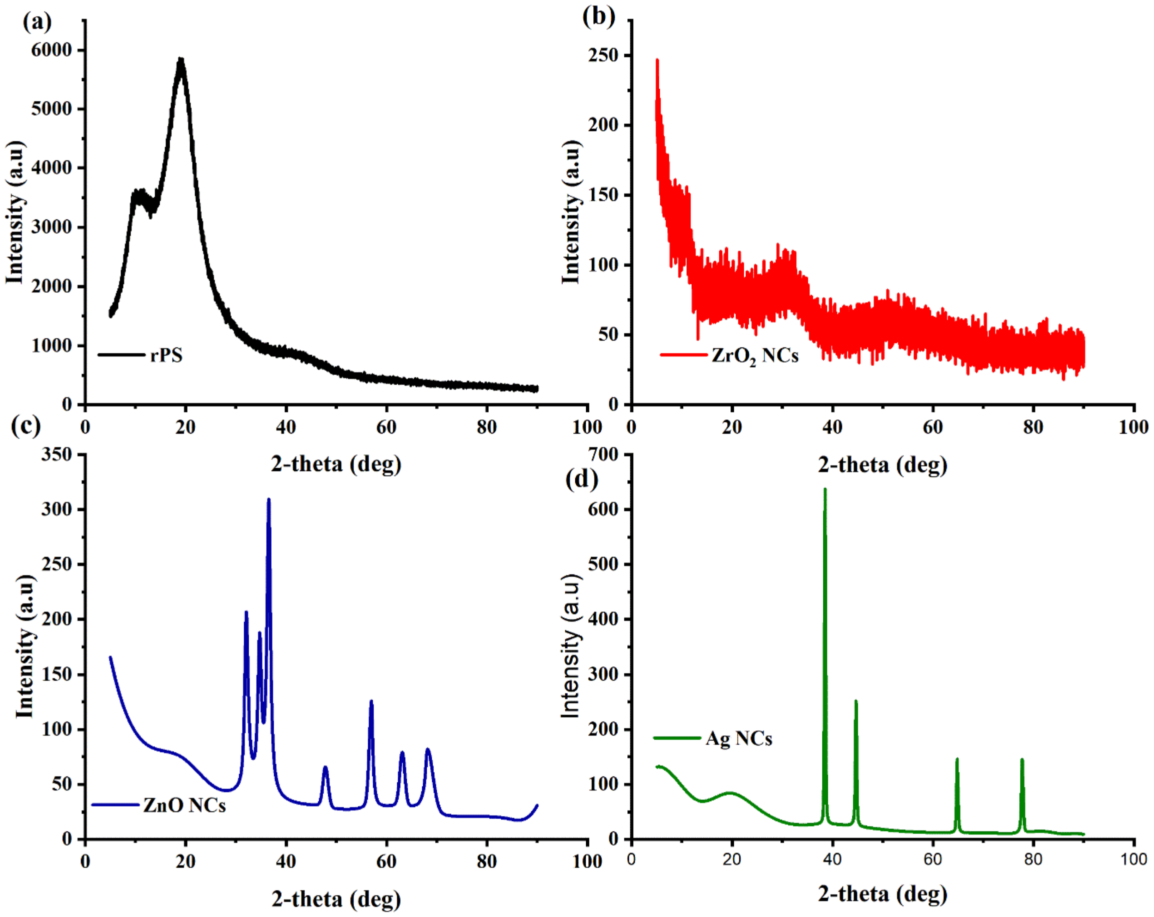


Figure 3: XRD spectra of (a) rPS, and (b) ZrO_2, (c) ZnO and (d) Ag NCs. Broad diffraction peaks for rPS are consistent with amorphous polystyrene, whereas diffraction patterns observed for the NCs are consistent with amorphous ZrO_2 and crystalline ZnO and Ag.

3.2.2 Thermal Gravimetric Analysis

Thermal gravimetric analysis (TGA) was employed to determine the amount of nanoparticles (inorganic fraction) in the NCs and the effect of the nanoparticles on the thermal stability of the rPS matrix (**Figure 4 and Figure 5**). As expected, for the rPS degradation begins at ~ 300 °C with a peak at ~400 °C and is almost completely converted to gaseous material (99.6 % weight loss) (**Figure 4**), which is consistent with the degradation of virgin polystyrene (Shah & Jan, 2015). In comparison, the ZrO_2, ZnO and Ag NCs showed a similar peak at ~400 °C resulting from the degradation of polystyrene, and upon heating to 600 °C the inorganic component was determined to be 52, 40 and 45% (**Figure 5**, **Table 1**), respectively. Given that ZrO_2, ZnO and Ag are thermally stable at temperatures greater than 600 °C, it was assumed that anything remaining at that temperature was the inorganic component. Interestingly, for the ZrO_2 NC, the onset of degradation appears to start slightly earlier (~250 °C), and there is a second clear degradation event at 550 °C (**Figure 4**). Previously, Mondal and Ram have shown that $ZrO(OH)_2.xH_2O$ decomposes to ZrO_2 at temperatures > 200 °C (Mondal & Ram, 2004). Therefore, the TGA results indicated the presence of mixed zirconium oxides/hydroxides in the ZrO_2 NC, which is consistent with the XPS and FTIR results.

When comparing the weight fraction of the inorganic component for the ZrO_2 and Ag NC determined by TGA with the weight fraction of insoluble components determined by dispersion of the NCs in THF (Žalmanová et al.), it is evident that a large fraction of the inorganic component is well-dispersed in the organic solvent (67, 71 and 67 % for the ZnO, ZrO_2 and Ag NCs, respectively) suggesting that the polystyrene matrix has a stabilising effect on the nanoparticles in solution. This characteristic makes these NCs particularly suitable for solution processing and could be used to prepare NC coatings via solvent casting, dip coating and spray coating.

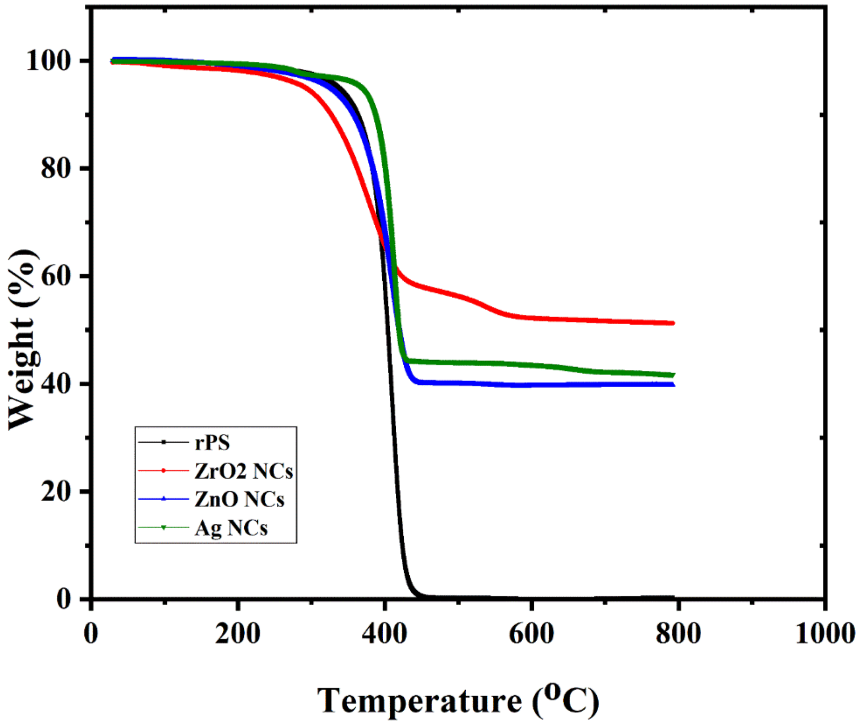


Figure 4: TGA thermograms curves for rPS, and the ZnO, ZrO2 and Ag NCs.

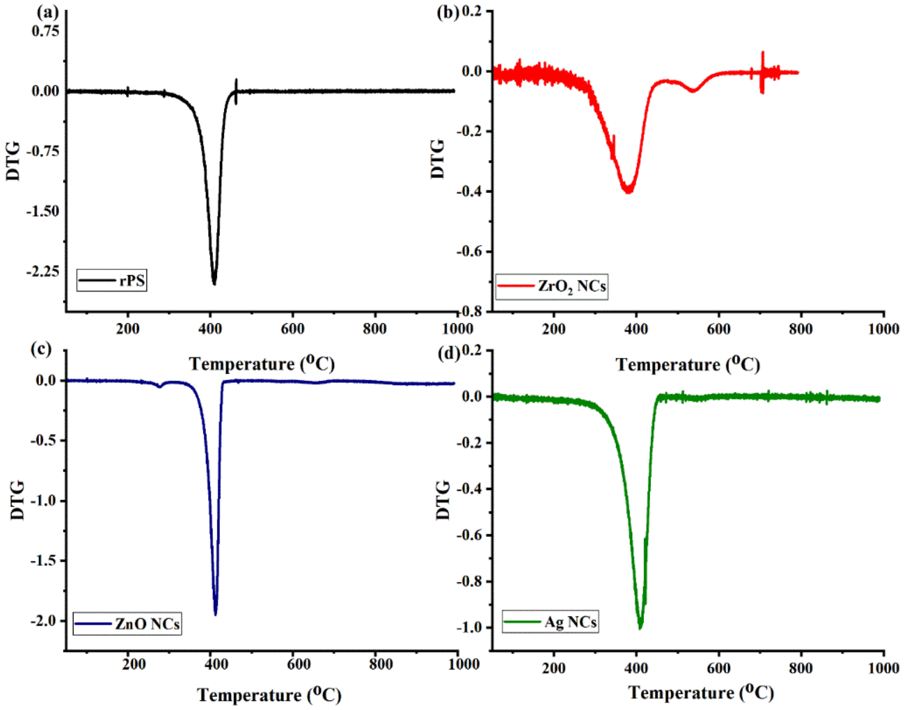


Figure 5: Normalised first derivative (DTG) curves for (a) rPS, (b) ZrO2, (c) ZnO and (d) Ag NCs.

Table 1: Characteristic degradation temperatures from TGA scans

Sample code	DLS particle size (nm)			TEM particle size (nm)	Insoluble fraction (wt%)[a]	Inorganic fraction (wt%)[b]
	Number	Intensity	Volume			
ZnO NC	9.3 ± 2.9	25.1 ± 13.5	13.1 ± 6.1	27.5 ± 19.6	14.9	45
ZrO_2 NC	411 ± 253	713 ± 433	918 ± 377	---	15.2	52
Ag NC	7.3 ± 2.2	18.3 ± 9.6	9.9 ± 4.4	13.4 ± 3.4	13.2	40

[a] Determined by dissolution of soluble fraction in THF. [b] Determined from TGA.

The influence of the nanoparticles on the crystallinity of the polystyrene matrix in the NCs was investigated via differential scanning calorimetry (DSC) (**Figure 6)**. In both the rPS and NCs, a large endothermic degradation peak (T_d) was noted between 390-435 °C, consistent with the TGA results. The broader degradation peak for the ZrO_2 NC can be attributed to the combined degradation of polystyrene and zirconium oxides/hydroxides. For rPS and the ZrO_2 NC, the glass transition temperature (T_g) was determined to ~100 °C, indicating that the ZrO_2 nanoparticles did not significantly influence the mobility or crystallinity of the polystyrene matrix in the NC. In comparison, the ZnO NC appeared to show two T_g values at 100 °C and 115 °C, and a peak at ~270 °C that was tentatively assigned to a melting temperature (T_m) of polystyrene. The T_m of virgin polystyrene is typically between 180 and 260 °C, which is slightly lower than that observed in the ZnO NC and implies that the nanoparticles retard melting of the polystyrene. The apparent increase in the T_m and the second T_g at 115 °C may be an indication of a unique interaction between the ZnO nanoparticles and the polystyrene or inclusion of the polystyrene within the nanoparticles. Similarly, the T_g determined at ~87 °C indicated that the Ag nanoparticles did not influence the mobility or crystallinity of the polystyrene matrix in the NC. The increase in the T_m of Ag NC may also be an evidence of an exclusive interaction between the Ag nanoparticles and the polystyrene matrix (**Figure 6**).

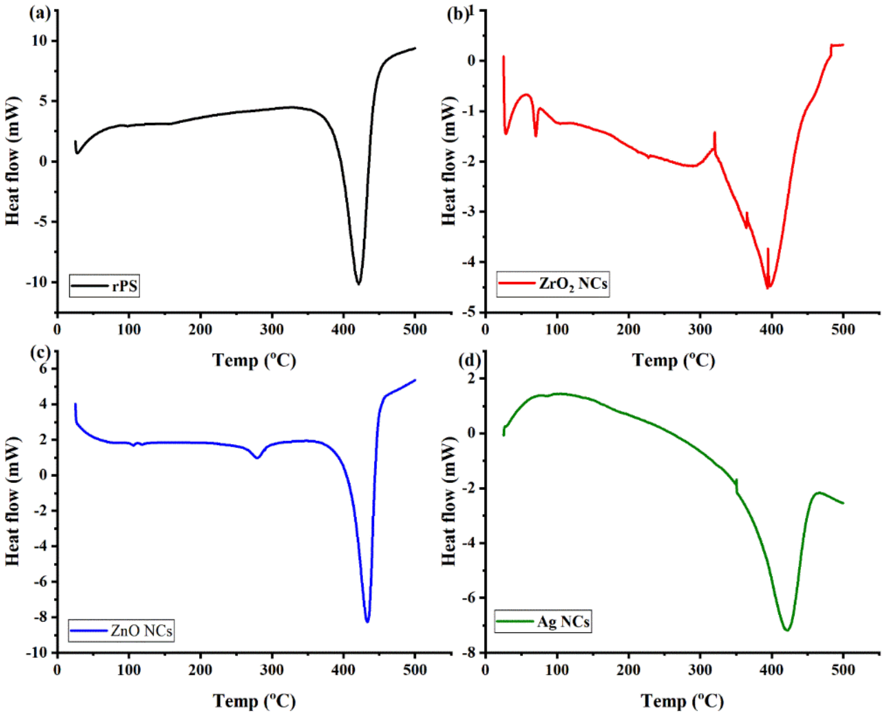


Figure 6: DSC thermograms for (a) rPS, and the (b) ZrO2, (c) ZnO and (d) Ag NCs.

Table 2: Characteristic degradation temperatures from DSC scans.

Sample	Characteristic temperatures from TGA scans		1st derivative	
	Ti/°C	Tf/°C	T/°C	Inorganic residues (%
rPS	300	420	409	0.6
ZrO_2 NCs	260	580	369	52
ZnO NCs	280	439	401	40
Ag NCs	250	430	405	45
$Zr(NO_3)_4$	29	592	45	45
$ZnCO_3$	230	279	95	95
$AgNO_3$	425	514	37	37

3.2.3 BET

The nitrogen adsorption-desorption isotherms for the rPS and NCs were recorded (**Figure 7**) and interpreted using Brunauer–Emmett–Teller (BET) theory to provide the surface area, pore size and pore volume (**Table 3**). The adsorption-desorption isotherm for rPS revealed a reversible Type II isotherm representative of a non-porous material and characteristics of polymeric materials such as polystyrene (Tsyurupa & Davankov, 2006). Similarly, the adsorption-desorption isotherm for the Ag NC revealed a Type II isotherm with a slight increase in pore volume compare to rPS, indicating that the nanoparticles are non-porous. In comparison, the ZrO_2 and ZnO NCs revealed Type IV isotherms with a hysteresis loop indicating that the nanoparticles are mesoporous, and resultantly there is also an increase in the pore volume.

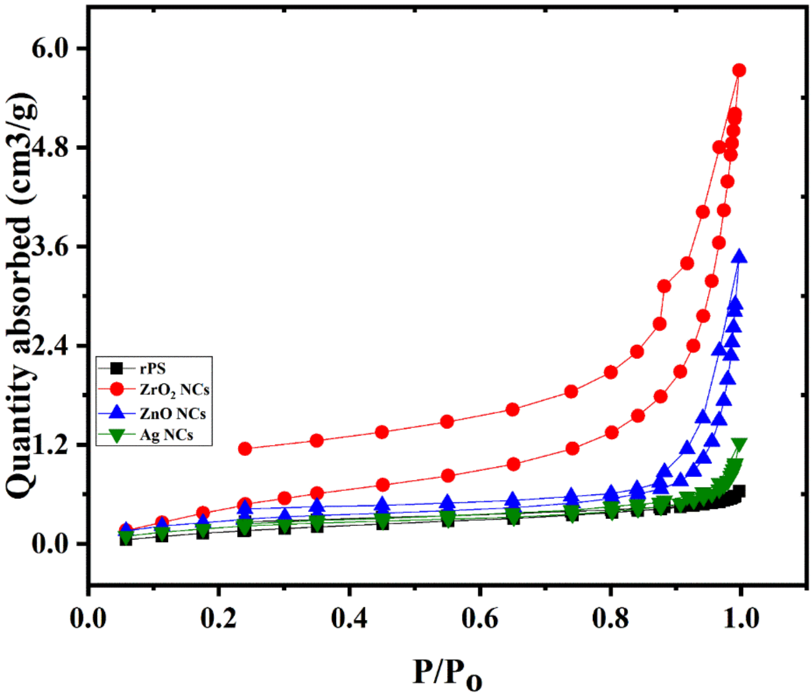


Figure 7: Volumetric N2 adsorption isotherms recorded at 77 K for the rPS, and ZrO2, ZnO and Ag NCs.

Table 3: BET analysis of rPS and NCs.

Sample	Characteristic temperatures from DSC scans		
	Tg/°C	Tm/°C	Td/°C
rPS	98	180/260	418
ZrO_2 NCs	98	280/320	392
ZnO NCs	100/115	272/362	430
Ag NCs	87	340	416

3.3 Morphological characterization

3.3.1 SEM

The morphologies of the rPS and NC powders were imaged via SEM (**Figure 8**). The images of rPS revealed folded sheet-like structures with relatively smooth topographies. In comparison, imaging of the ZrO_2 and ZnO NCs displayed aggregated platelet structures, whereas the Ag NCs have a foam-like structure. Therefore, it is evident that the incorporation of the inorganic nanoparticles into the PS matrix impacts the morphology of the isolated powders.

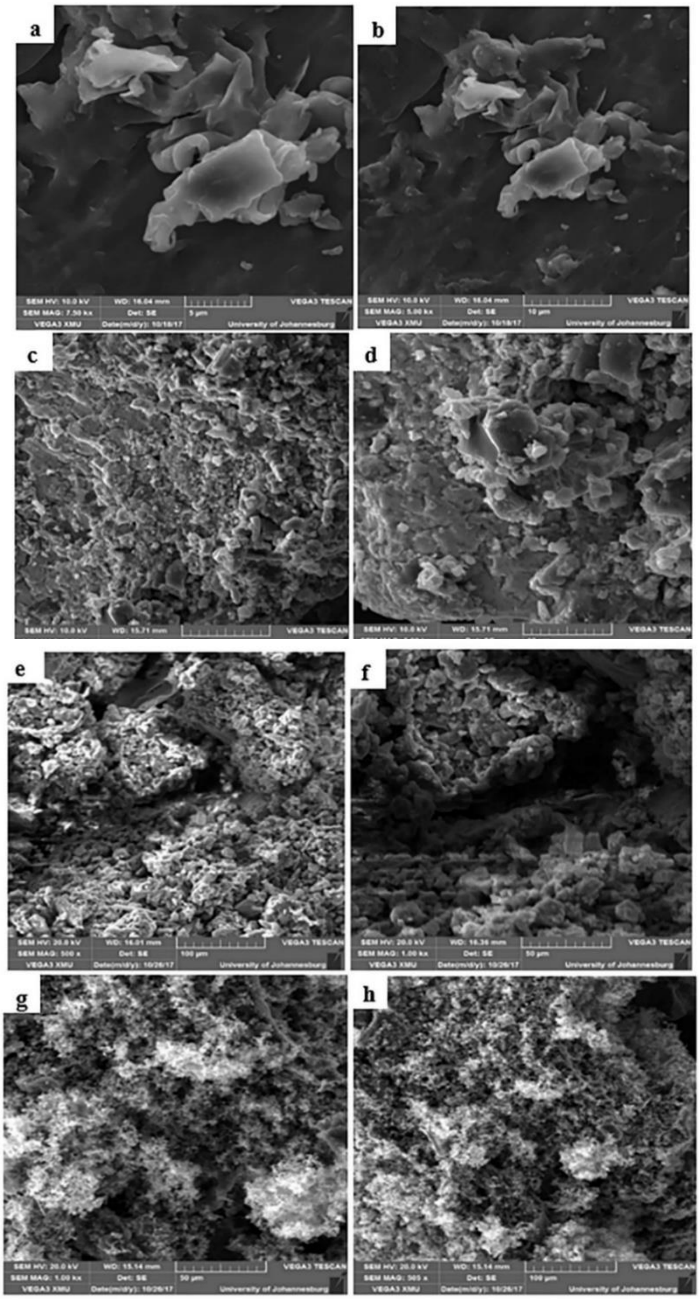
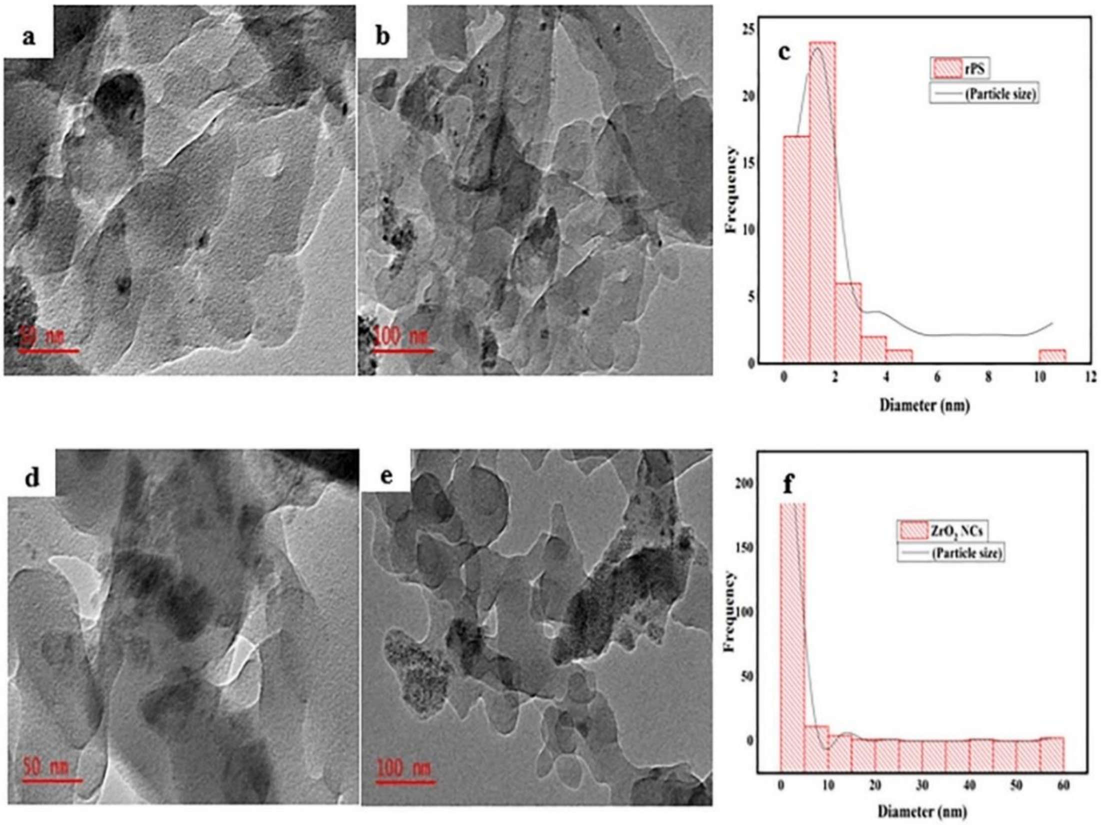


Figure 8: SEM images of (a,b) rPS, and (c,d) ZrO2, (e,f) ZnO and (g,h) Ag NCs. Whereas rPS displays smooth sheet-like structures, the NCs display aggregated platelet or foam-like structure.

3.3.2 TEM

The size, shape and distribution of the nanoparticles within the PS-based NCs were studied using TEM (**Figure 9**). For the ZnO NCs, aggregates of quasi-spherical nanoparticles were observed dispersed throughout the PS matrix. In comparison, large and irregular features were observed only in certain areas of the PS matrix for the ZrO_2 NCs. For the Ag NCs, well-dispersed and spherical nanoparticles were observed in the polystyrene matrix. Whilst measurement of the particle diameter from the TEM images for the Zn and Ag NCs provided values of 27.5 ± 19.6 and 13.4 ± 3.4 nm, respectively, the poor contrast and irregular shape of the ZrO_2 particles made determination of their size difficult. From these results it is evident that the PS matrix stabilizes compositionally different nanoparticles to varying degrees, and that the solvothermal process produces NCs with broad particle size distributions.



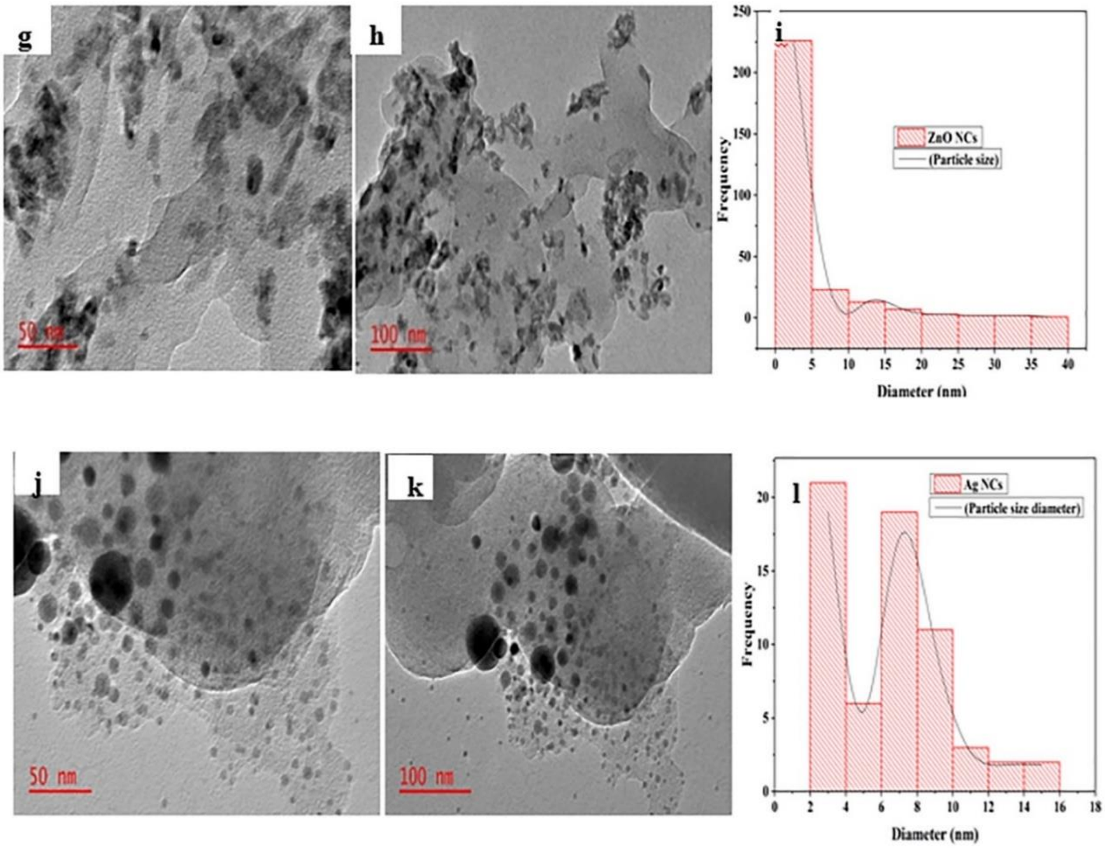


Figure 9: TEM images of (a,b) rPS, (d,e) ZrO2, (g,h) ZnO, and (i,j) Ag NCs. Whereas the ZnO and Ag NCs clearly show dispersed nanoparticles with a relatively large particle size distribution, much larger particles or aggregates are observed for the ZrO2 NC. Scale bars represent 50 nm (a,d,g,j) and 100 nm (b,e,h,k) and (c,f,i,l) represent the particle size diameter (PSD).

3.3.3 DLS

To further characterize the nanoparticle component of the NCs, the organic soluble fraction was extracted and analyzed by dynamic light scattering (DLS). This was also expected to provide an indication of how well-dispersed the nanoparticles were in the polystyrene matrix and whether the nanoparticles could be dispersed in solution. Therefore, the NCs were mixed with THF (a good solvent for the polystyrene component), the insoluble fraction was separated via centrifugation, and the soluble fraction was analysed via DLS

(**Table 4** and SI, **Figure S12**). The intensity distribution of the DLS results for the soluble fractions of the ZnO and Ag NCs revealed nanoparticles with particle 25.1 ± 13.5 and 18.3 ± 9.6 nm, respectively, which is consistent with the TEM results. The slightly lower particle sizes provided by the number and volume distributions may result from the irregular particle shapes (ZnO NC) and broad particle size distributions. For the soluble fraction of the ZrO_2 NC, the intensity distribution provided particle sizes of 713 ± 433 nm, which may result from the formation of large aggregates as indicated in the TEM images.

Table 4: Particle sizes of nanoparticles in the NCs determined by DLS and TEM, and insoluble and inorganic mass fraction.

Samples	Type of Isotherm	Surface area (m^2/g	Pore size nm	Pore volume (cm^3/g)
rPS	Type II	0.8029	3.8933	0.000782
ZrO_2 NCs	Type IV	2.3291	12.7502	0.007424
ZnO NCs	Type IV	1.1034	13.1228	0.003620
Ag NCs	Type II	0.8590	5.3060	0.001139

4. Conclusion

In this study we introduce a facile and cheap solvothermal process for the *in-situ* preparation of high filler content nanocomposites from waste polystyrene and readily available inorganic precursors. Specifically, zirconia (ZrO_2), zinc oxide (ZnO) and silver (Ag) nanocomposites were prepared with high filler content (~40-50%), although this approach could conceivably be extended to other waste plastics and inorganic nanoparticles. The solvothermal technique allowed the hydrophilic ZrO_2, ZnO and Ag nanoparticles to be homogenously dispersed in the hydrophobic rPS matrix. This strategy may ultimately prove usefulness for the economical repurposing of waste plastics to provide value added materials. For ZnO and Ag nanocomposites, the average particle diameters are ~ 20-30 nm and quite broad particle size distributions were observed, whereas the ZrO_2 nanocomposite consisted of significantly large particles/aggregates, indicating that the composition of the inorganic precursor/filler and its interaction with the polystyrene matrix plays an important role in controlling nanoparticle formation. In combination with the type of inorganic fillers used in this study, the synthesised nanocomposites may be applicable in photocatalysis.

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Compliance with Ethical Standards

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Conflict of Interest: The authors declare that they have no known conflicting financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that they have no conflict of interest.

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Supporting Information

^{1}H-NMR spectroscopy

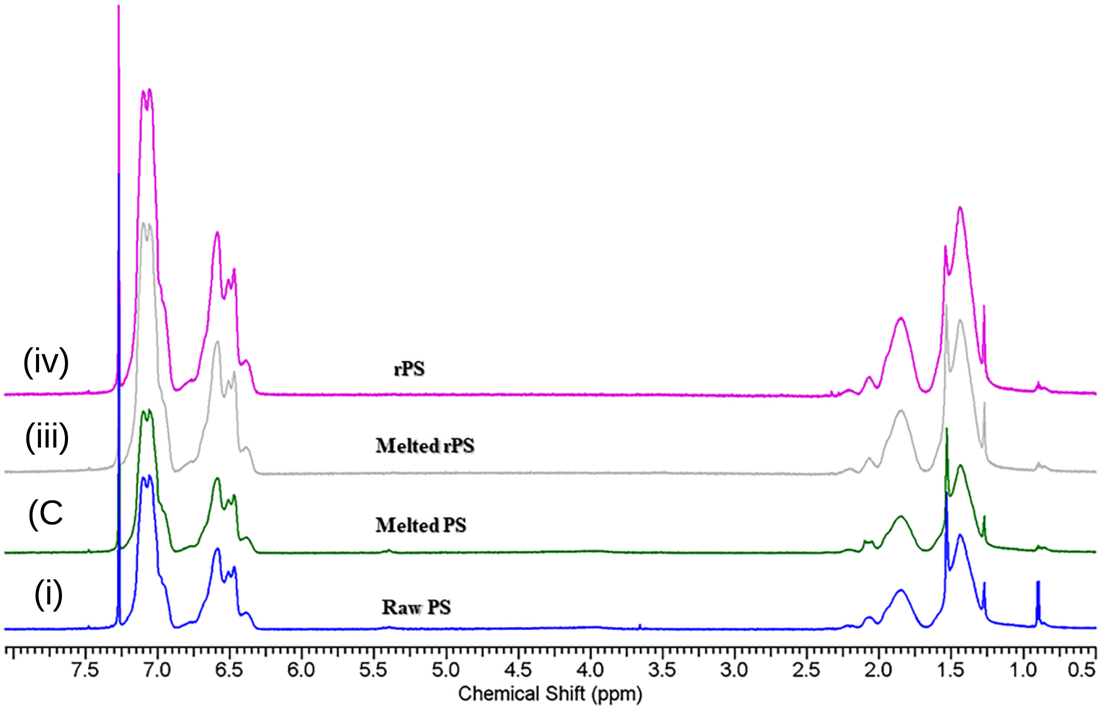


Figure S 1: ^{1}H NMR spectra (500 MHz, $CDCl_3$) of (i) raw waste PS, melt processed raw waste PS, (iii) melt processed rPS, and (iv) rPS.

Structural evidence was studied from ^{1}H-NMR using the four different samples. The four spectra obtained showed that there was no chemical shift in the polymer. Moreover, it was observed from the spectra that the polymers are of aromatic rings and all their signals are doublets which showed that a hydrogen atom is coupled to two non-equivalent hydrogen atoms. The peaks at δ~1.0–2.0 ppm is an indication that these polymers are assigned to methylene ($-CH_2-$) and methane protons. Similarly, the multiple peaks from δ~6.3–7.2 ppm are because of the resonance of aromatic phenyl group protons.

Gel permeation chromatography (GPC)

Table S 1: Weight-average molecular weight (M_w), number-average molecular weight (M_n) and **dispersity (*Đ*) determined from gel permeation chromatography.**

	Raw waste PS	Melt processed raw waste PS	rPS	Melt processed rPS
M_w (kDa)	260	227	181	243
M_n (kDa)	153	134	96.7	117
Đ	1.7	1.7	1.9	2.1

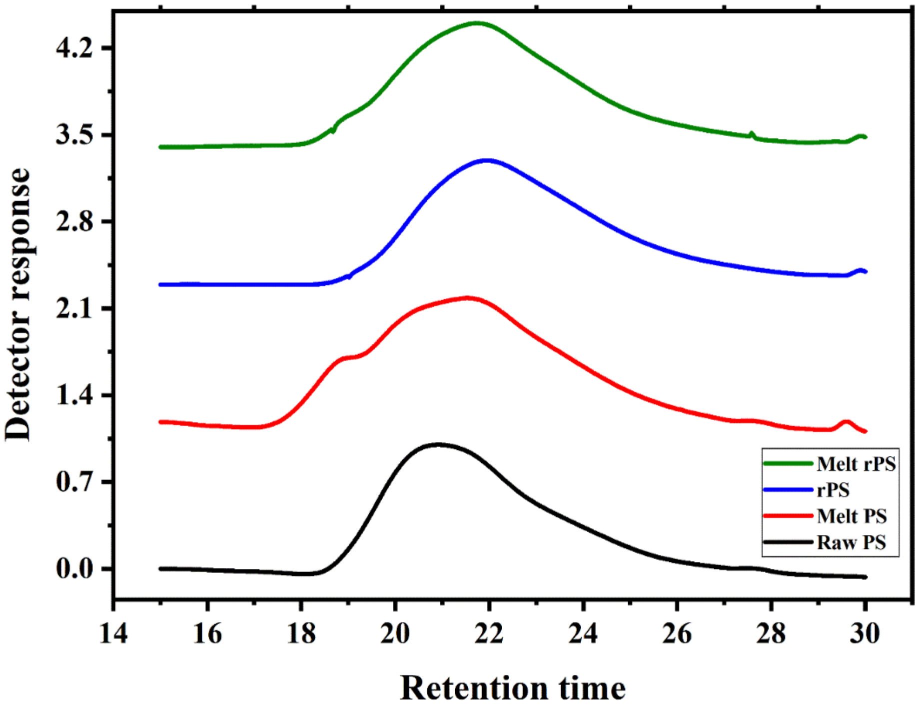
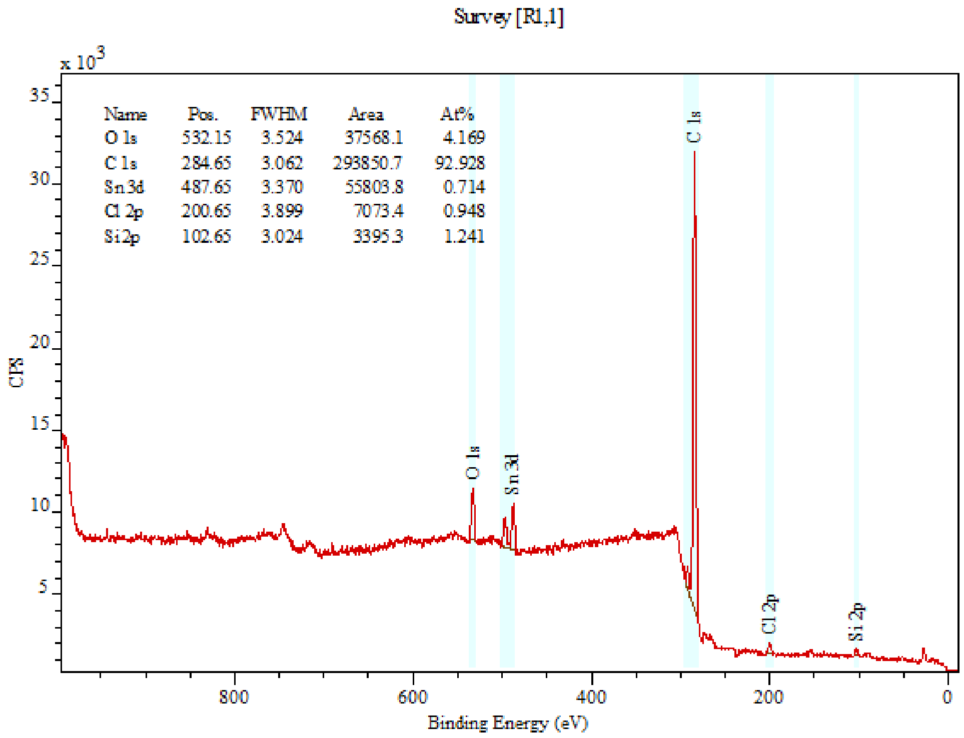


Figure S 2: GPC differential refractive index chromatograms for different polymer samples.

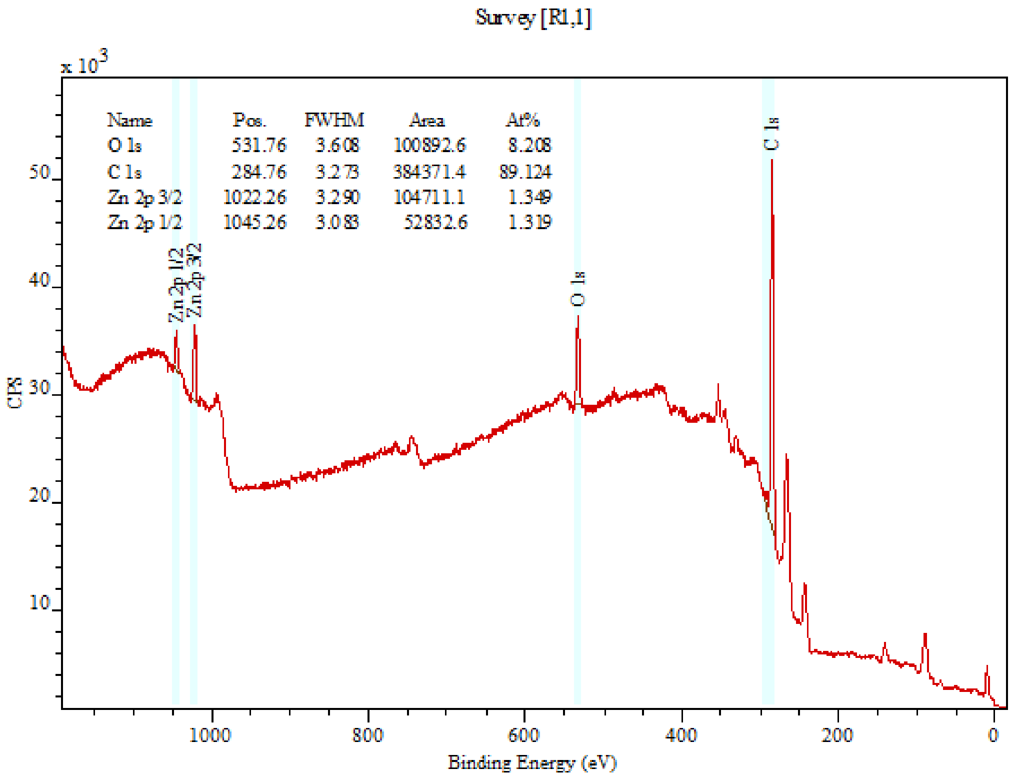
The purpose of the GPC measurement is to determine the molecular weight (Mw) distribution of polymers dispersed in an organic solvent. The Mw of the raw PS and the melted PS alongside their PDI values were consistent. There are discrepancies in the data for rPS and melted rPS. There is only one major at about 21 min that is common to all the four samples. This shows that there is only one size distribution of molecular weight for all the four samples. Hence, the results showed there is no significant changes in the structure of the polymers.

X-ray photoelectron spectroscopy (XPS)



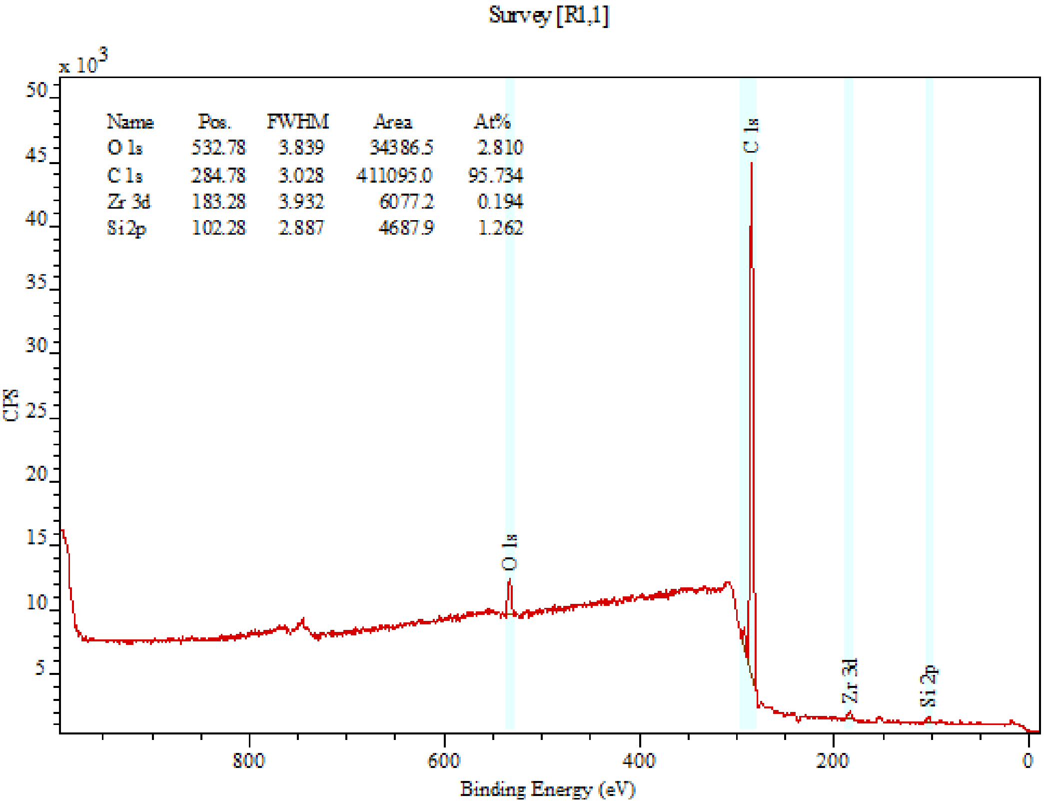
Name	Pos.	FWHM	Area	At%
O 1s	532.15	3.524	37568.1	4.169
C 1s	284.65	3.062	293850.7	92.928
Sn 3d	487.65	3.370	55803.8	0.714
Cl 2p	200.65	3.899	7073.4	0.948
Si 2p	102.65	3.024	3395.3	1.241

Figure S 3: XPS survey spectra of rPS.



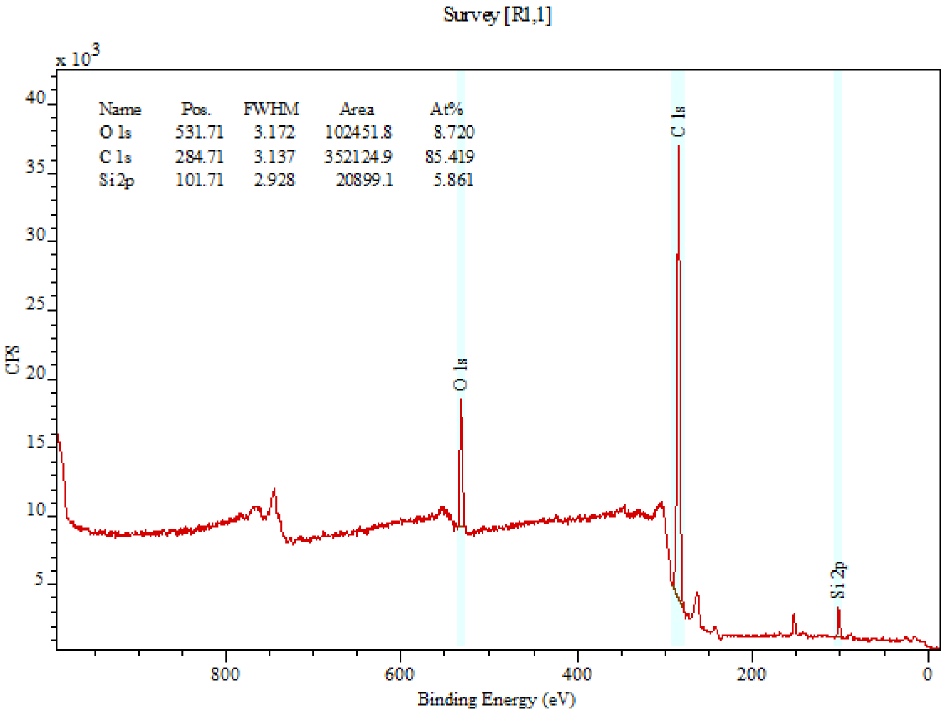
Name	Pos.	FWHM	Area	At%
O 1s	531.76	3.608	100892.6	8.208
C 1s	284.76	3.273	384371.4	89.124
Zn 2p 3/2	1022.26	3.290	104711.1	1.349
Zn 2p 1/2	1045.26	3.083	52832.6	1.319

Figure S 4: XPS survey spectra of ZnO NC.



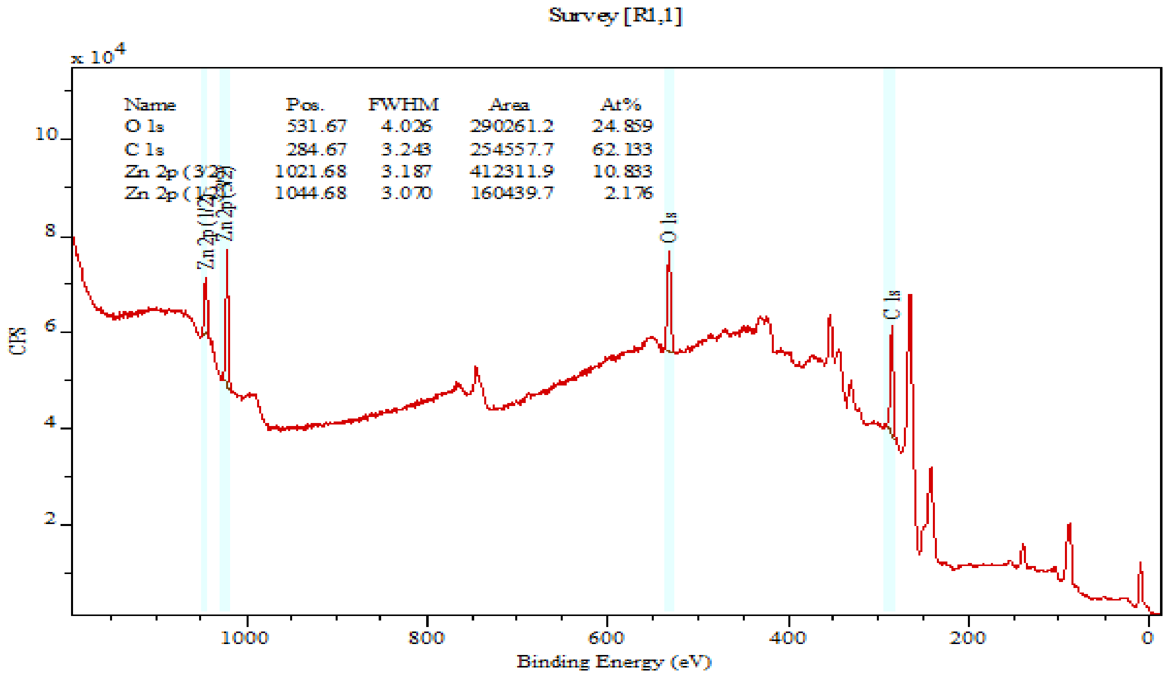
Name	Pos.	FWHM	Area	At%
O 1s	532.78	3.839	34386.5	2.810
C 1s	284.78	3.028	411095.0	95.734
Zr 3d	183.28	3.932	6077.2	0.194
Si 2p	102.28	2.887	4687.9	1.262

Figure S 5: XPS survey spectra of ZrO_2 NC.



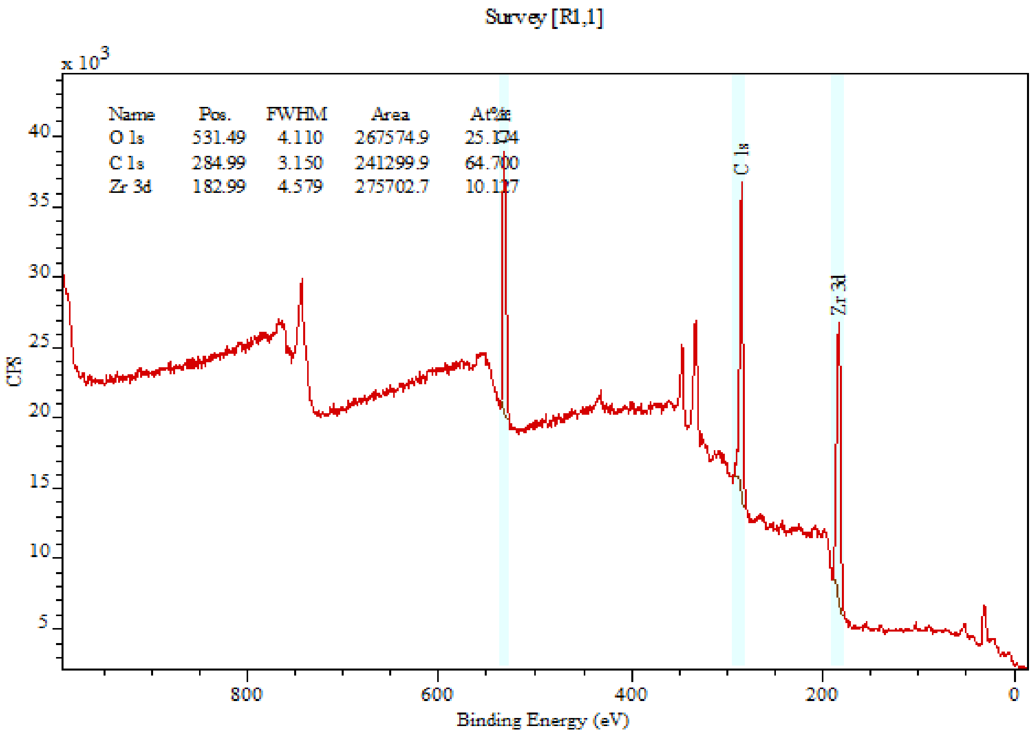
Name	Pos.	FWHM	Area	At%
O 1s	531.71	3.172	102451.8	8.720
C 1s	284.71	3.137	352124.9	85.419
Si 2p	101.71	2.928	20899.1	5.861

Figure S 6: XPS survey spectra of Ag NC.



Name	Pos.	FWHM	Area	At%
O 1s	531.67	4.026	290261.2	24.859
C 1s	284.67	3.243	254557.7	62.133
Zn 2p (3/2)	1021.68	3.187	412311.9	10.833
Zn 2p (1/2)	1044.68	3.070	160439.7	2.176

Figure S 7: XPS survey spectra of the insoluble fraction from the ZnO NC.



Name	Pos.	FWHM	Area	At%
O 1s	531.49	4.110	267574.9	25.174
C 1s	284.99	3.150	241299.9	64.700
Zr 3d	182.99	4.579	275702.7	10.127

Figure S 8: XPS survey spectra of the insoluble fraction from the ZrO_2 NC.

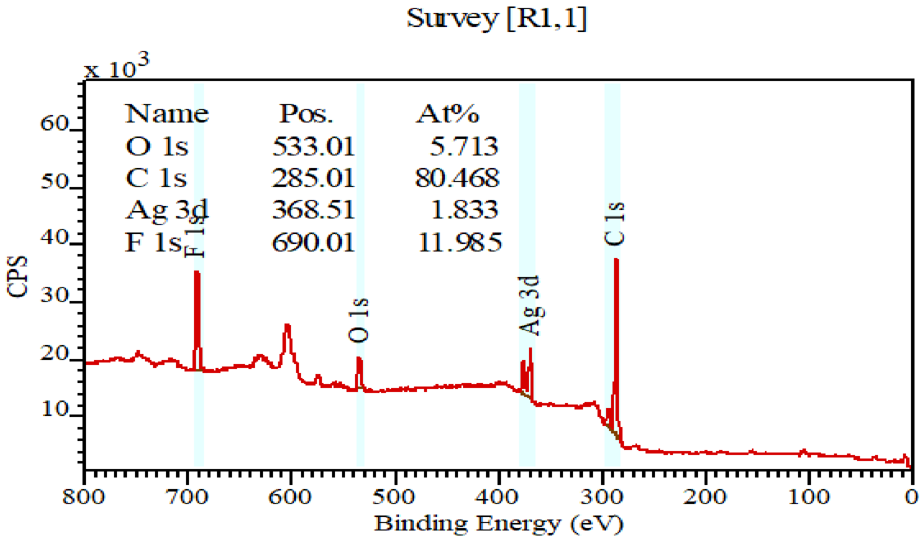


Figure S 9: XPS survey spectra of the insoluble fraction from the Ag NC.

Table S 2: Elemental composition from XPS peak areas (survey) for rPS.

	C 1s (%)	O 1s (%)	Sn 3d (%)	Cl 2p (%)	Si 2p (%)	C/O
PS	92.93	4.17	0.71	0.95	1.24	22.29

Table S 3: Elemental composition from XPS peak areas (survey) for ZrO_2 NC and isolated insoluble inorganic component.

	C 1s (%)	O 1s (%)	Zr 3d (%)
ZrO_2 NC	95.73	2.81	0.19
Isolated ZrO_2	64.70	25.17	10.13

Table S 4: Elemental compositions from XPS peak areas (survey) for ZnO NC and isolated insoluble inorganic component.

	C 1s (%)	O 1s (%)	Zn 2p 3/2 (%)	Zn 2p 1/2 (%)
ZnO NC	89.12	8.21	1.35	1.32
Isolated ZnO	62.13	24.86	10.83	2.18

Table S 5: Elemental compositions from XPS peak areas (survey) for Ag NC and isolated insoluble inorganic component.

	C 1s (%)	O 1s (%)	Ag 3d (%)
Ag NC	85.42	8.72	
Isolated Ag	80.47	5.71	1.83

Table S 6: Elemental composition from high-resolution XPS peak areas for insoluble ZrO_2 according to deconvolution shown in Figure 1.

	O 1s (%)	O 1s (%)	O 1s (%)	Zr 3d (3/2) (%)	Zr 3d (5/2) (%)
ZrO_2	32.05	53.40	14.55	59.48	40.52

Table S 7: Elemental composition from high-resolution XPS peak areas for insoluble ZnO according to deconvolution shown in Figure 1.

	O 1s (%)	O 1s (%)	Zn 2p (3/2) (%)	Zn 2p (1/2) (%)
ZnO	47.75	52.25	67.87	32.13

Table S 8: Elemental composition from high-resolution XPS peak areas for insoluble Ag according to deconvolution shown in Figure 1.

	Ag 3d (5/2) (%)	Ag 3d (3/2) (%)	Ag 3d (5/2) (%)	Ag 3d (5/2) (%)
Ag	52.31	35.77	6.974	4.95

X-ray diffraction (XRD)

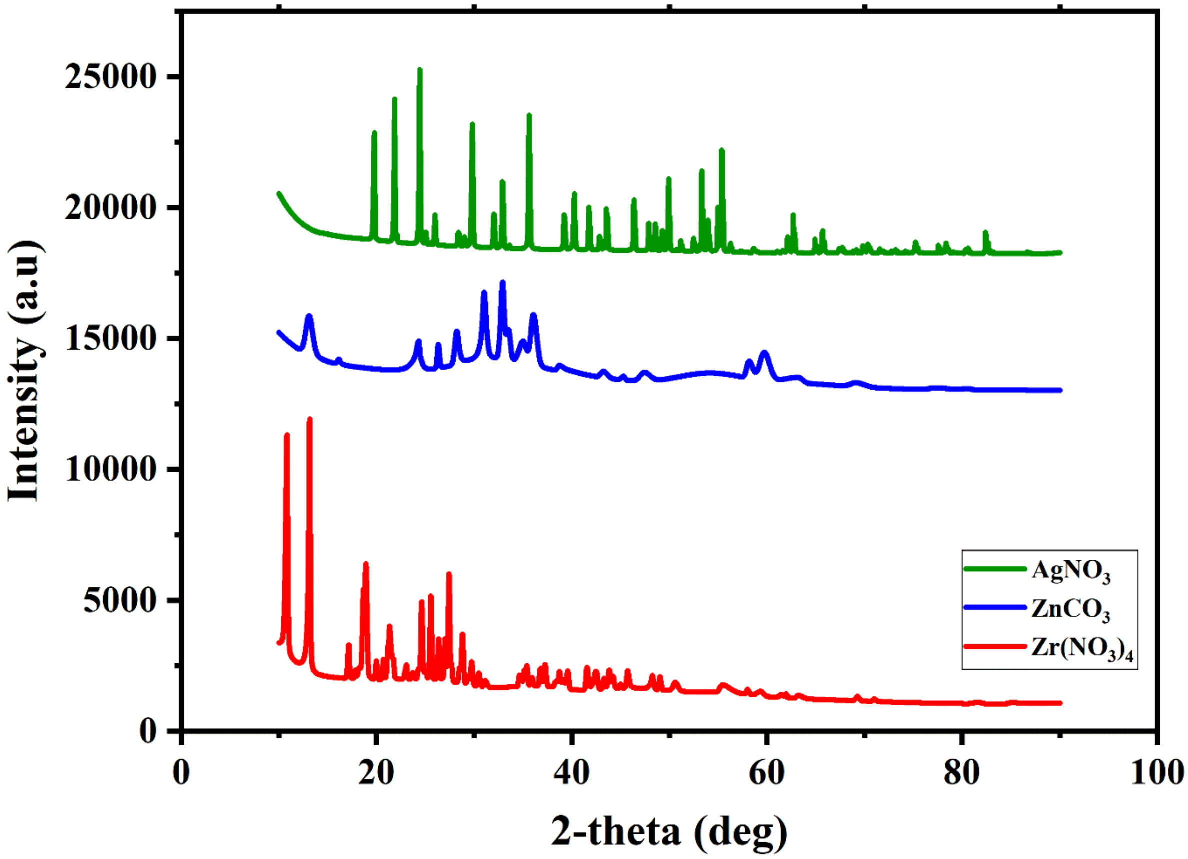


Figure S 10: XRD spectra for Zr(NO$_3$)$_4$, ZnCO$_3$ and AgNO$_3$.

Fourier-transform infrared (FTIR) spectrophotometry

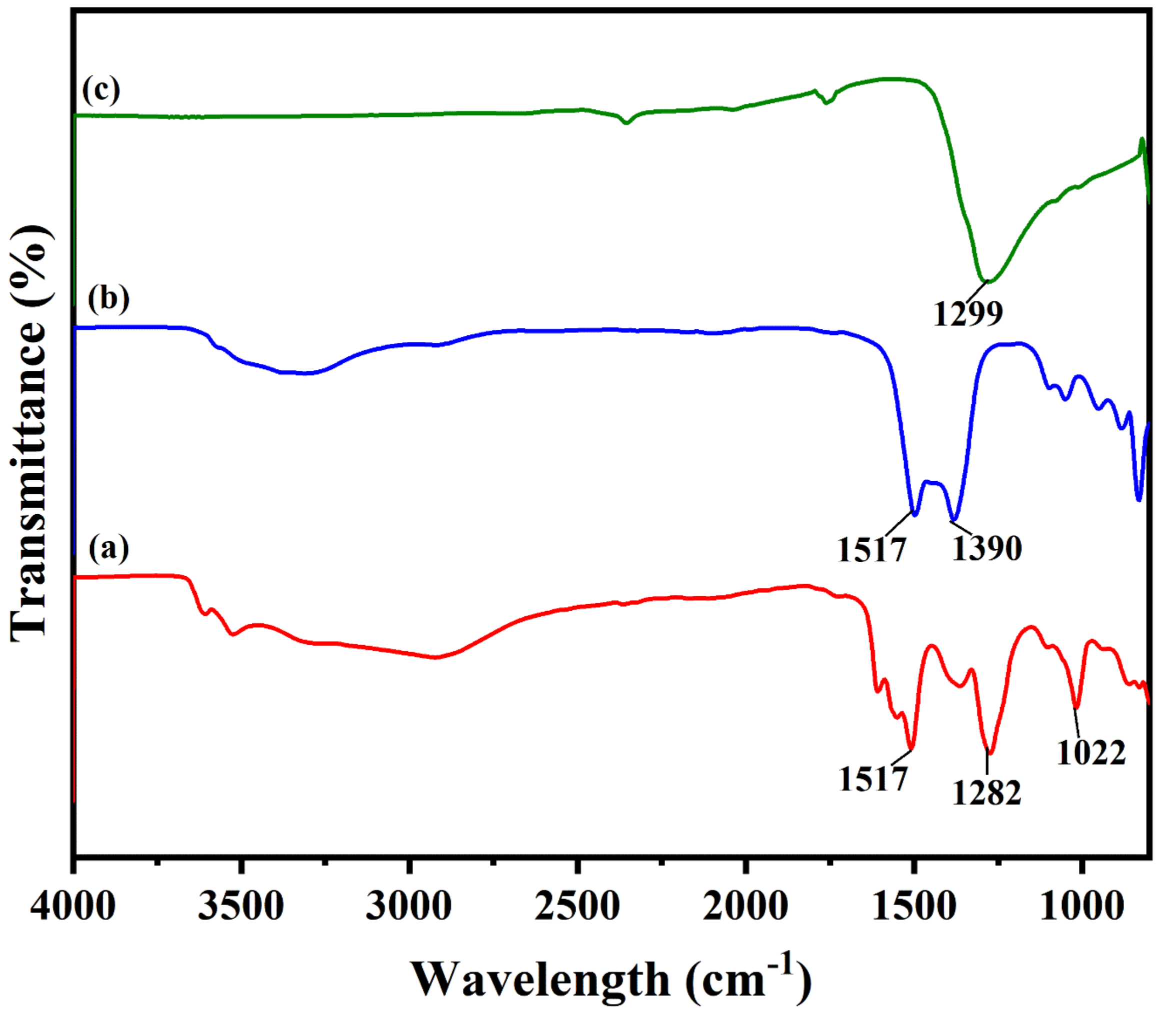


Figure S 11: FTIR spectra for $Zr(NO_3)_4$, $ZnCO_3$ and $AgNO_3$.

Dynamic light scattering

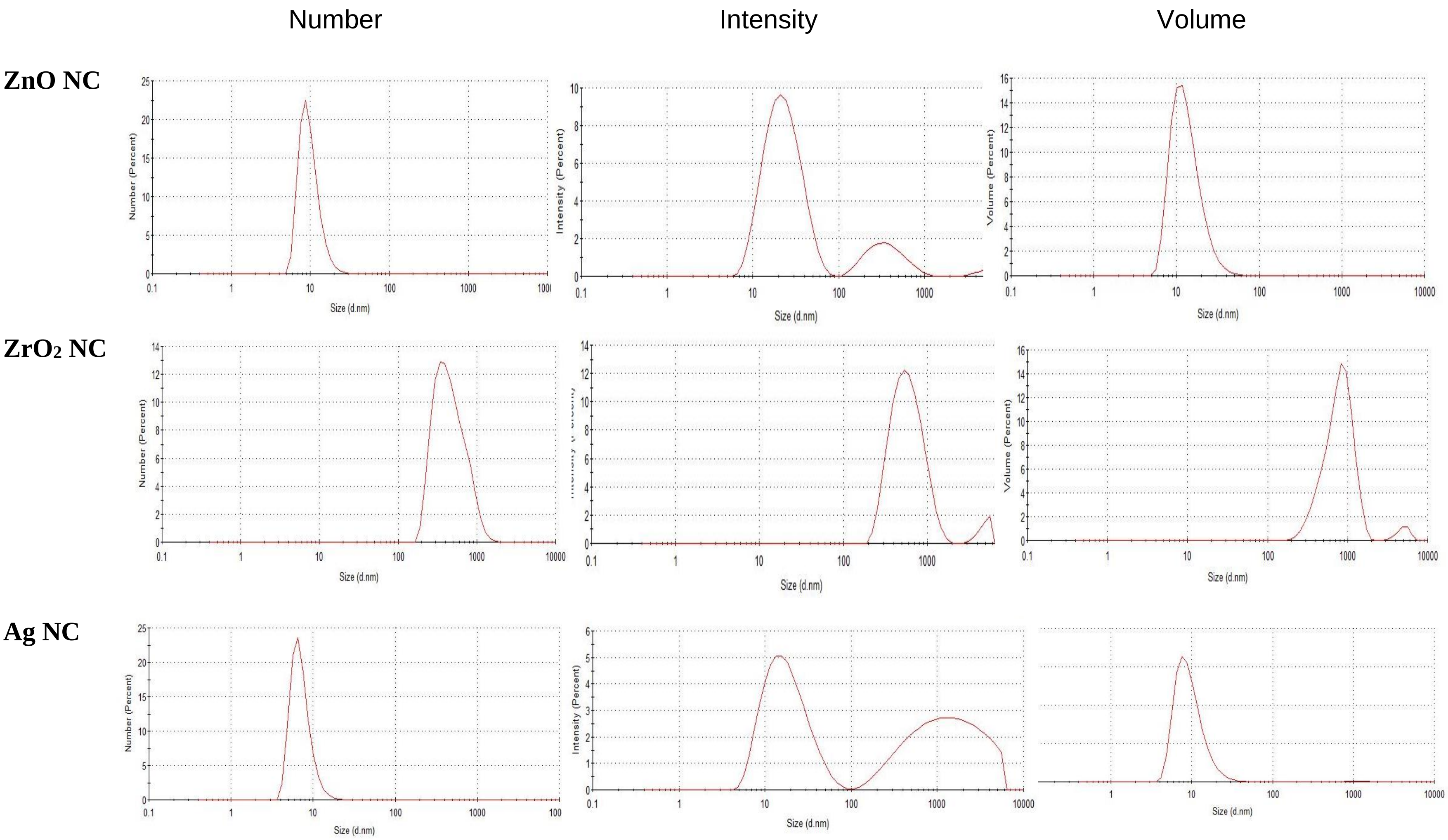


Figure S 12: DLS number, intensity and volume plots for ZnO, ZrO_2 and Ag NC

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Nanoindentation studies and characterization of hybrid nanocomposites based on solvothermal process

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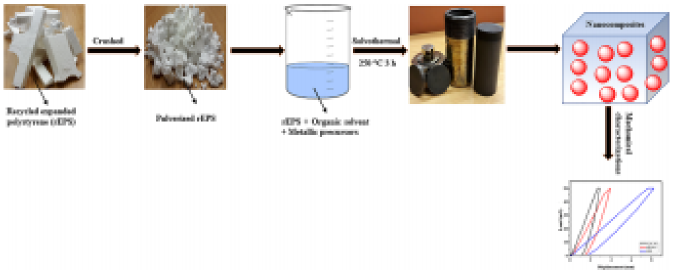
GRAPHICAL ABSTRACT



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ABSTRACT

Recycling of waste polymers by the combination of polymer wastes with metallic precursors is a thread which has not been given wide attention by researchers. In this study, we reported on the evaluation of mechanical properties of hybrid nanocomposites via nanoindentation technique. Hybrid organic/inorganic nanocomposites consisted of recycled expanded polystyrene (rEPS) (organic polymer); $Fe(NO_3)_3 \cdot 9H_2O$ and $Zn(NO_3)_2 \cdot 6H_2O$ (metallic precursors) were developed through solvothermal method. The hybridized nanocomposites obtained were characterized by different techniques, comprising X-ray diffraction (XRD), Fourier transform-infrared (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM) with particle size distribution (PSD) and Selected area (electron) diffraction (SAED) pattern, thermogravimetric (TGA) analysis and nanoindentation technique. The results obtained showed the hybrid Fe_2O_3 NCs under the 20 mN indentation load were having the best indentation depth of 0.5 nm, nanohardness of 1.20 GPa, reduced modulus of 8.20 GPa, elastic strain recovery of 0.18 GPa and anti-wear resistance of 0.025 GPa. The applicability of the hybrid NCs was demonstrated via the enhancement of their mechanical properties.

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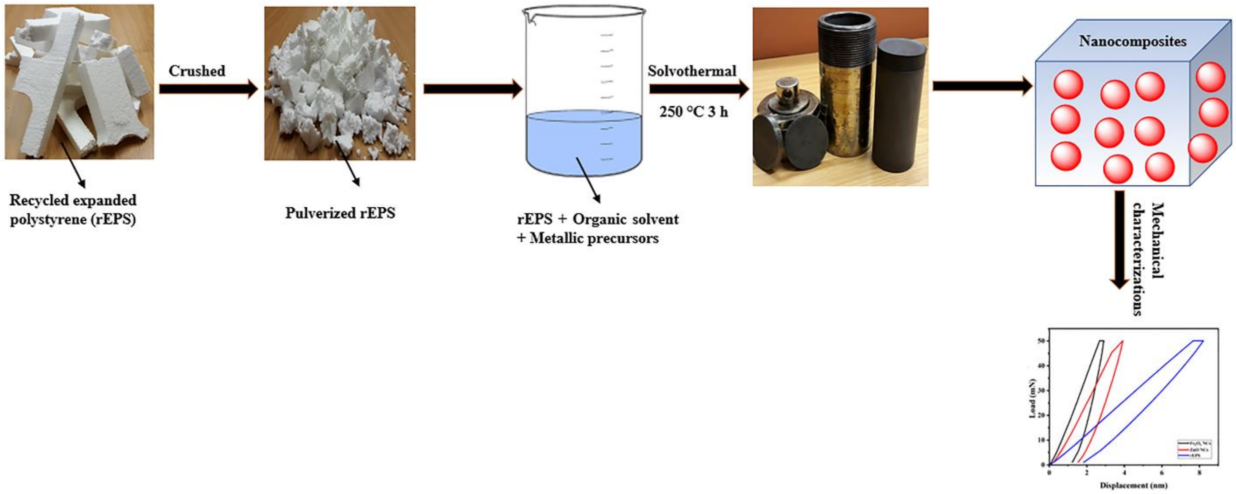

Abstract

Recycling of waste polymers by the combination of polymer wastes with metallic precursors is a thread which has not been given wide attention by researchers. In this study, we reported on the evaluation of mechanical properties of hybrid nanocomposites via nanoindentation technique. Hybrid organic/inorganic nanocomposites consisted of recycled expanded polystyrene (rEPS) (organic polymer); $Fe(NO_3)_3.9H_2O$ and $Zn(NO_3)_2.6H_2O$ (metallic precursors) were developed through solvothermal method. The hybridized nanocomposites obtained were characterized by different techniques, comprising X-ray diffraction (XRD), Fourier transform-infrared (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM) with particle size distribution (PSD) and Selected area (electron) diffraction (SAED) pattern, thermogravimetric (TGA) analysis and nanoindentation technique. The results obtained showed the hybrid Fe_2O_3 NCs under the 20 mN indentation load were having the best indentation depth of 0.5 nm, nanohardness of 1.20 GPa, reduced modulus of 8.20 GPa, elastic strain recovery of 0.18 GPa and anti-wear resistance of 0.025 GPa. The applicability of the hybrid NCs was demonstrated via the enhancement of their mechanical properties.

Keywords:

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1. Introduction

The multi-hydra facets challenges of recycling of plastic waste has been ‘a thorn in the flesh’ issues confronting many nations of the world with respect to production and consumption of plastic materials. It has become very crucial to design a new and functional hybrid materials such as nanocomposite (NC) with enhanced properties [1] to mitigate this issue. NC comprises of two or more materials with diverse physical and chemical properties to form a novel material, improved version of individual component materials with the new products having a grain size below 100 nm [2]. Recently, organic and inorganic materials have gained attention extensively in the development of NCs owing to their special features [3, 4]. For instance, inorganic material is rigid and thermally stable, and the organic material is flexible, ductile and processable [5]. The major reason for employing inorganic materials in NC could be due to their physical, thermal and chemical properties which in most cases improve the structural integrity of new products. While on the other hand, organic compounds are the starting material in the synthesis of plastic [6]. Plastic materials are obtained from petroleum products and are usually illustrated by long chain hydrocarbon molecules or its starting material [7]. A recent study has shown that the production of plastics will reach over ~400 million tonnes by 2020 [8]. This implies that increase in production growth rate is directly proportional to the consumption rate, thus making their management method a bit challenging and is usually very poor and unsustainable. Therefore, plastic waste (PW) tend to accumulate at the disposal sites rather than degrading since the materials are usually non-biodegradable [9]. The continuous accumulation of plastic materials at the disposal facilities is causing serious health and environmental issue and on account of this, the constant production and consumption of plastic materials have become sources of huge of concern to policy-makers globally [10]. In a bid to ameliorate the health and environmental issues connected with the poor disposal of plastics waste (PW), several investigators have lately incorporated inorganic precursors into polymer matrices materials (by impregnating inorganic material into a polymer) to produce polymer composites of improved version with better properties compared to the original individual component materials [11]. The incorporation of inorganic precursors into the polymer composites has been very crucial to numerous applications recently [12].

Furthermore, one of the vital inorganic precursors that has been of valuable usage is Iron (III) Nona hydrate nitrate [$(Fe(NO_3)_3.9H_2O$]. This is a solid, purple and odourless powder with a melting point temperature of around 47 ℃ [13]. This inorganic powder material [$Fe\ (NO_3)_3.9H_2O$] can be incorporated into several polymers and the resulting products would be Iron (III) oxide (Fe_2O_3) NC. Ordinarily, Fe_2O_3 particle has magnetic features and this magnetic nanomaterial has several applications such as data storage, lubricants, wave absorbers, therapeutic agent in cancer treatment and drug delivery. The magnetic features of this nanomaterial are of immense relevance in biomedical application, nevertheless, the plain superparamagnetic nanomaterial requires encrust using materials with a highly soluble, biocompatible and non-hazardous materials and polystyrene material has been recommended as an appropriate candidate where recycled expanded polystyrene (rEPS) acts as a surface coat on Fe_2O_3 to fabricate hybrid Fe_2O_3 NCs with diverse applications [14-16].

Similarly, zinc nitrate hexahydrate [$Zn(NO_3)_2.6H_2O$], an important precursor is usually employed for the synthesis of zinc oxide (ZnO) nanomaterials. It is an odourless white solid material with a melting point of around 36 ^{o}C and a specific gravity of 2.065 [17]. This material has a strong oxidizing agent that makes it to react vigorously with any reducing agent. Hence, when an inorganic filler is added to the polymer, the resultant product is ZnO NC. ZnO NCs have wide range of applications in semiconductors, solar cells, catalysts, pigments, electronics, gas sensors and photocatalysis [18, 19]. ZnO NC is an expansive band gap semiconductor having disproportionate thermal, chemical and mechanical stability. Its physical and chemical properties are also very high, and its energy gap is 3.37 eV. Due to its distinctive properties which include, catalytic, electrical, optoelectronic and photochemical, ZnO is currently applied in many fields [20-22]. Its unique areas of applications comprise pharmaceuticals, sunscreens, food flavours, colourants and electrical materials [23, 24]. ZnO is also used to enhance the tribological properties of the polymeric matrices when the thermal conductivity of polymeric materials changes [25].

Therefore, it is expected that this present study would be helpful in addressing the issue of the structures of plastic polymer material (PPM) which is often degraded thereby leaving poor thermal and mechanical properties resulting from poor PW management. Taking into consideration the importance of the development of nanocomposites using organic-inorganic material, it can be said that there has been little, or no study carried out till date on the fusion of recycled expanded polystyrene (rEPS)/inorganic metals via solvothermal technique to produce nanocomposites while evaluating the mechanical properties of the nanocomposites.

2. Experimental

2.1. Materials

Iron (III) nitrate nonahydrate [$Fe (NO_3)_3 . 9H_2O$, ≥99.95% trace metals basis], Chloroform (99.8% assay, $(CH_3)_2CO$ 0.005%, Iodine 0.001%) and Zinc nitrate ($Zn(NO_3)_2.6H_2O$ (98% assay, Lead 0.02%, iron 0.001%, chloride 0.005%) were purchased from Glassworld & Chemical Suppliers CC, South Africa. All chemicals were used as received. Laboratory blender (OmniBlend I-2ltr Pro, TM767) was from OminiBlend, South Africa, and mortar and pestles from Glassworld & Chemical Suppliers CC, South Africa. Milli-Q water was used for cleaning of glassware. The recycled expanded polystyrene (rEPS) was collected from a recycling facility in Doornfontein, Johannesburg, South Africa. A solvothermal autoclave reactor (250 mL) with a Teflon cup was purchased from Protea Laboratory Solution (Pty) Ltd, Johannesburg, South Africa.

2.2. Method

The samples were prepared according to Youssef et al. [26] and Herrera-Sandoval et al. [27] methods with slight modifications. The method is described briefly as follows; rEPS (10.00 g) was dissolved into chloroform (100 mL) and sonicated for 15 min at room temperature. The sample was transferred into a Teflon cup (250 mL), covered and placed inside a solvothermal autoclave reactor and placed in an oven at 250 °C for 3 h. After cooling to ambient temperature, synthesized rEPS sample was obtained as a brown powder. Similarly, a hybrid metallic Fe_2O_3 NCs was produced from the solvothermal synthesis of recycled expanded polystyrene (rEPS) (organic polymer) and inorganic fillers [(Fe $(NO_3)_3$. $9H_2O$)] (precursor). Sample was prepared by the dispersion of rEPS (10.00 g) into the chloroform solution (organic solvent). Sample was sonicated for 15 min. Afterwards, Fe $(NO_3)_3$. $9H_2O$ (5.00 g) was added into the solution and sonicated for another 15 min. The sample was placed inside the Teflon cup of the autoclave reactor, sealed and placed in an oven pre-heated at a temperature of 250 ºC and left for 3h. Finally, a resulting product of dried powdered-greyish/purple coloured Fe_2O_3 NC was obtained. The same procedure was repeated for the combination of rEPS (10.00 g) with $Zn(NO_3)_2.6H_2O$ (5.00 g) and ZnO NC was obtained. The resulting samples were pulverized into powder using mortar and pestle and the powdered samples were used for further analysis.

2.3. Characterization techniques

2.3.1. Compositional, structural and thermal analysis

XRD analysis was used to investigate the crystallinity of the synthesized samples. This was carried out on X- ray diffractometry (PANalytical Empyrean) with Cu-Kα1 radiation. The chemical structures and functional groups present in the rEPS, Fe_2O_3 NCs and ZnO NCs were studied using Fourier Transform Infrared Spectroscopy (FTIR) characterization technique. The sample was monitored using the Thermo Scientific FTIR apparatus (Australia) with specific Range 4000 cm^{-1} to 500 cm^{-1}) in absorption mode, using samples prepared as KBr discs. Scanning electron microscopy (SEM) was performed on a VEGA3 TESCAN, 20 mm^2 at 20 kV. The NCs were pulverized, sieved using ASTM standard sieves and were sputter coated to evaporate a thin layer of carbon on the surface of the sample. Each of the samples was individually mounted onto a holder with the aid of double-sided carbon tape. The double-sided carbon tape was fixed on a glass slide and samples glued to the carbon tape. The glass slides were pressed, and samples were loaded into SEM chamber for analysis. The Energy Dispersive X-Ray (EDX) attached to the Scanning electron microscopy (SEM) (VEGA3 TESCAN, 20 mm^2 at 20 kV) was used to identify the elemental composition of the samples. Transmission electron microscopy (TEM) was performed on a JEOL JEM-2100 at a voltage of 200 kV. The samples were prepared by adding a few powders to 100% ethanol and sonicated for 10 min. A few drops of freshly prepared suspension were added on to a carbon coated copper (Cu) grid allowing the solvent to evaporate and the TEM images were taken. Selected area (electron) diffraction (SAED) pattern images were also taken. The particle size diameters (PSDs) were evaluated from the TEM images using ImageJ software with 100 shells on the rEPS composites and the NCs and the averaged size distribution of the samples were obtained. The thermal stability of the NC was performed on

Thermogravimetric Analyzer Discovery TGA 550 under a nitrogen atmosphere (10 mL/min) at 10 °C/min heating rate between ambient temperature and 1000 °C.

2.3.2. Mechanical properties

Nanoindentation methods are used for the evaluation of mechanical characteristics of polymeric materials. To estimate these properties via nanoindentation technique, several factors are put into consideration, some of which are shown in **Fig. 1**. The nanoindentation tests were carried out on the NC discs with the aid of an ultra-micro indentation system (UMIS) 2000 nanoindenter (Future Industries, University of South Australia, Australia) at room temperature using a Berkovich indenter with an angle of 65 º, initial contact of 0.05 mN, a hold time of 60 s, and a Poissons ratio of 0.33. NCs powdered samples were heated in an oven at 160 °C for 30 min and were hydraulically compressed (10 tonnes) into discs for analysis. The chamber of the investigation was kept at 9 x 10^{-7} Pa (a pressure lesser compared to the pressure of the chamber) during measurements. The NC discs were mounted on a stainless steel-sample holder using silicon glue. Three different loads (20, 50 and 100 mN) at constant rates were used to carry out the tests for all samples. Before the experiment commenced, calibration was made based on established methods. Afterwards, a usual loading-hold-unloading cycle occurred. The surface of the samples was later engaged, and the indentation load was raised at an interval till a known maximum load is reached. During the unloading, the tip is retracted from top of sample at the equal time. A minimum of five indents were carried out on various spots on each sample.

The following parameters are defined as: the indentation depths, h_t represent the total depth under a load, P_t; h_e is elastic recovery depth during the unloading, h_f is residual impression depth, h_a is surface displacement at the perimeter and h_p is the contact indentation depth. Moreover, contact stiffness S, is expressed as the slope at the beginning of the unloading curve and is given as follows;

$$S = \frac{dp}{dh} \qquad (1)$$

Also, according to the Oliver-Pharr approach, the contact stiffness (S), the indented area (A) at maximum load and the reduced elastic modulus E_r can be given by the following equation as; [28].

$$S = \frac{2}{\sqrt{\pi}} Er\sqrt{A} \qquad (2)$$

Equating equations (2) and (3), we now have an expression as;

$$S = \frac{dp}{dh} = \frac{2}{\sqrt{\pi}} Er\sqrt{A} \qquad (3)$$

The elastic modulus (E) is therefore evaluated as;

$$Er = \frac{\sqrt{\pi}}{2}\frac{dp}{dh}\frac{1}{\sqrt{A}} \qquad (4)$$

Furthermore, E_r is given in terms of poisson's ratio of materials (v_s), indenter (v_i), elastic modulus of materials (E_s), indenter (E_i) and is denoted as;

$$\frac{1}{Er} = \frac{1 - v^2}{E} + \frac{1 - vi^2}{Ei} \qquad (5)$$

where, E_r is the reduced modulus of indentation contact, E_i (1140 GPa) and vi (0.07) are the elastic modulus and Poisson's ratio of the indenter. E_r can also be presented as;

$$Er = \frac{S}{2}\frac{\sqrt{\pi}}{\sqrt{24.5\mathrm{hc2}}} \qquad (7)$$

Where A is given as $24.5h_c^2$ which can be obtained from the projected area of Berkovich indenter as discussed by Okoro et al. [29].

In the same way, hardness, H, is obtained from the loading curve and is represented as the maximum normal load, P_{max}, divided by A (the projected contact area at the maximum load) and is given by; [30].

$$H = \frac{\mathrm{Pmax}}{A} \tag{8}$$

Besides, there is an expression connecting hardness H, reduced modulus E_r and contact stiffness S at the maximum load (i.e. combining equation 2 and equation 8) and we are thus given;

$$H = \frac{4PmaxEr^2}{\pi S^2} \tag{9}$$

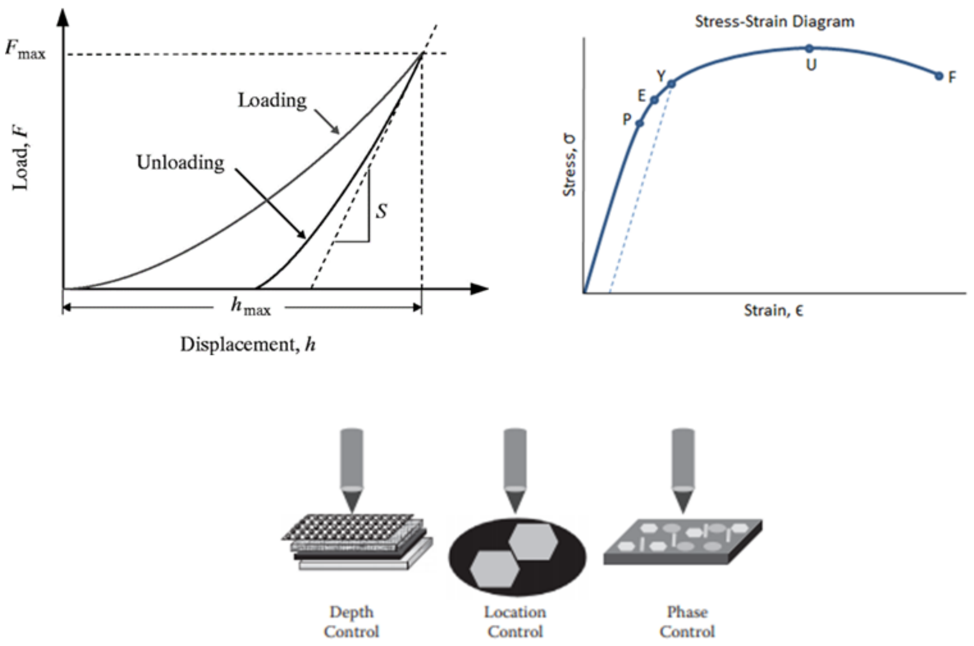


Figure 1: Factors for the determination of mechanical properties of materials via nanoindentation technique.

3. Results and discussion

3.1. Preparation of samples

The preparation of the synthesized recycled expanded polystyrene (rEPS) material (control experiment) and the hybrid nanocomposites (NCs) was carried out using a solvothermal method as shown in **Fig. 2.** For the rEPS sample preparation, no precursor was added to the solution. Sample was dissolved in an organic solvent and transferred to an autoclave reactor and placed in an oven pre-heated at a temperature of 250 ºC for 3 h. Afterwards, a brown powdered (97.4%) was gotten. Similarly, Fe_2O_3 and ZnO NCs were obtained from the impregnation of rEPS with Fe $(NO_3)_3$. $9H_2O$ and rEPS with $Zn(NO_3)_2.6H_2O$ respectively. The entire process was repeated with the inclusion of metallic precursors. Finally, hybrid Fe_2O_3 NCs (purple coloured, 79.84%) and ZnO NCs (dark brown coloured, 80.99%) powdered samples were obtained. The solvothermal approach was chosen for the preparation of the NCs since it affords NCs of suitable dimensions.

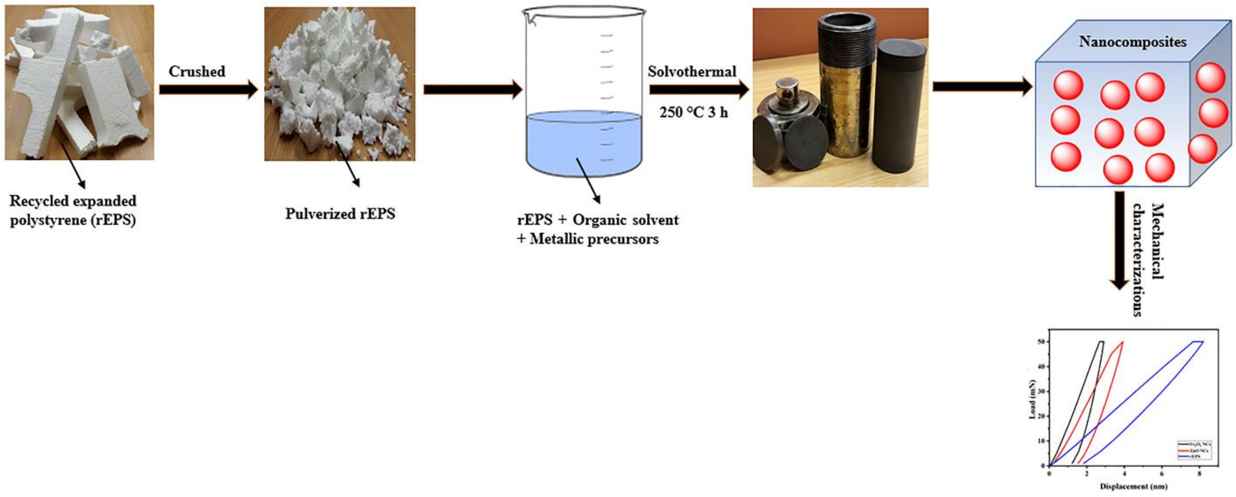


Figure 2: Schematic illustration of the synthesis of hybrid nanocomposites via solvothermal method.

3.2.Characterization of nanocomposites

XRD analysis is used to determine the crystallinity and crystalline phases of materials. **Fig. 3** shows the XRD pattern for rEPS, Fe_2O_3 NCs and ZnO NCs. The broad peaks at 10.19º [corresponding to (100)] and 19.91º [corresponding to (200)] of 2θ **(Fig. 3a)** matches the crystal planes of polystyrene. The polystyrene spectrum is partly amorphous and partly crystalline in nature with the peak at 10.19º confirming amorphous sample and 19.91º indicating crystallinity material [31]. **Fig. 3b** showed the XRD pattern for Fe_2O_3 NC with a peak located at 19.39º indicated that polystyrene is present in the sample as a carrier [32]. The lack of Braggs peaks in the XRD pattern is an indication that the prepared Fe_2O_3 NC is an amorphous material [33]. The amorphous nature of the NC can be transformed into crystalline by heating the prepared NCs in oxygen to obtain γ-Fe_2O_3 NC or via heating in a vacuum (nitrogen) at a temperature of around 420

°C to obtain Fe_3O_4 NC [34]. The summary of some of the phases is shown in **Table S1** (**Supplementary Information, SI**). **Fig. 3c** showed the peaks for ZnO NCs synthesised via the impregnation of rEPS and $Zn(NO_3)_2.6H_2O$ at 32.03º, 34.62º, 36.49º and 47.66º of 2θ which relate to (100), (002), (101) and (102) [35]. The list of other phases is shown in **Table S2** (**Supplementary information**, SI). These results confirmed the wurtzite structure of the ZnO NCs [36]. No other peaks were noticed in the spectrum which shows the superior quality of the synthesized NCs.

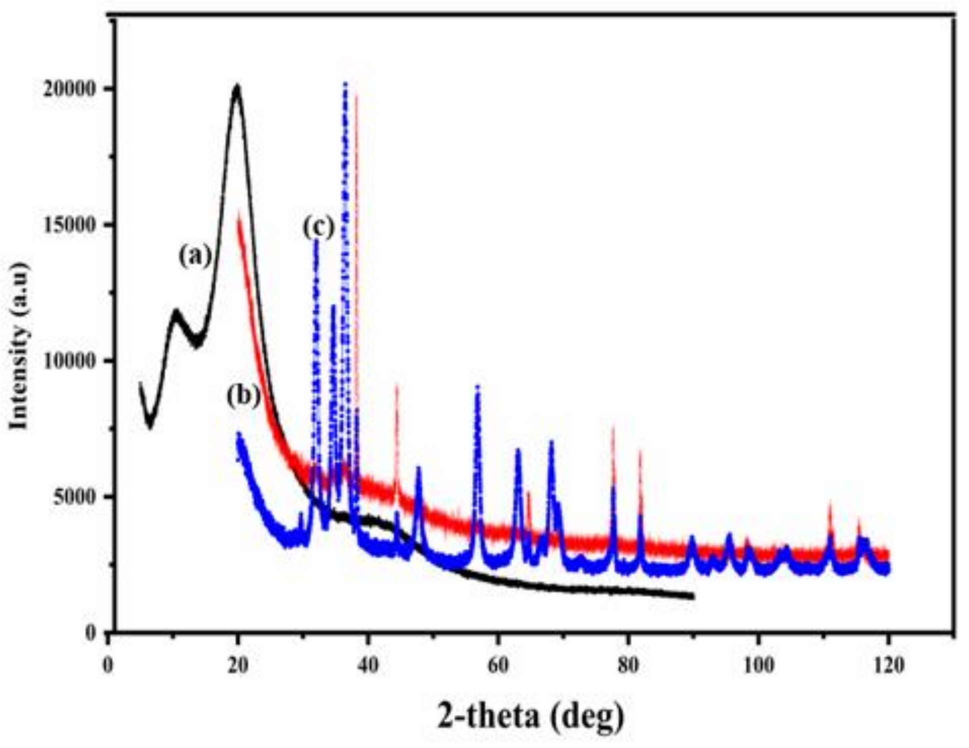


Figure 3: X-ray diffraction pattern for a) rEPS; b) Fe2O3 NCs and c) ZnO NCs.

3.3. Fourier Transform Infrared Spectroscopy (FTIR)

The chemical structures and functional groups present in the NCs were studied using FTIR spectroscopy. The FTIR spectra (**Fig. 4**) showed the rEPS, Fe_2O_3 NCs and ZnO NCs. The spectra for rEPS (**Fig. 4a**) showed peaks at 3032, 2941, 1494 and 1383 cm^{-1} which are typical characteristics of polystyrene (PS). The peaks at 3032 and 2941 cm^{-1} are because of the stretching and bending vibrations of the C-H bonds. The band around 1600 - 1369 cm^{-1} are because of the aliphatic C-H bending. For the Fe_2O_3 NCs (**Fig. 4b**), peaks formed at 3032, 2910, 1602, 1494 cm^{-1} were like that of the polystyrene. The peaks at 2910 and 2837 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrations of $–CH_2$ group respectively. The absorption band varying at 3032 cm^{-1} is due to aromatic C-H stretching vibration. The bands at 1602 - 1454 cm^{-1} are due to the aromatic C=C from styrene units. Also, the presence of the ZnO NCs (**Fig. 4c**) does not affect the functional group except for the peaks from 3047 to 2857 cm^{-1} that have almost disappeared when compared with the polystyrene spectra but there were no new peaks formed. It is therefore concluded that Fe_2O_3 NCs and ZnO NCs do not create chemical bonds with the functional groups of polystyrene.

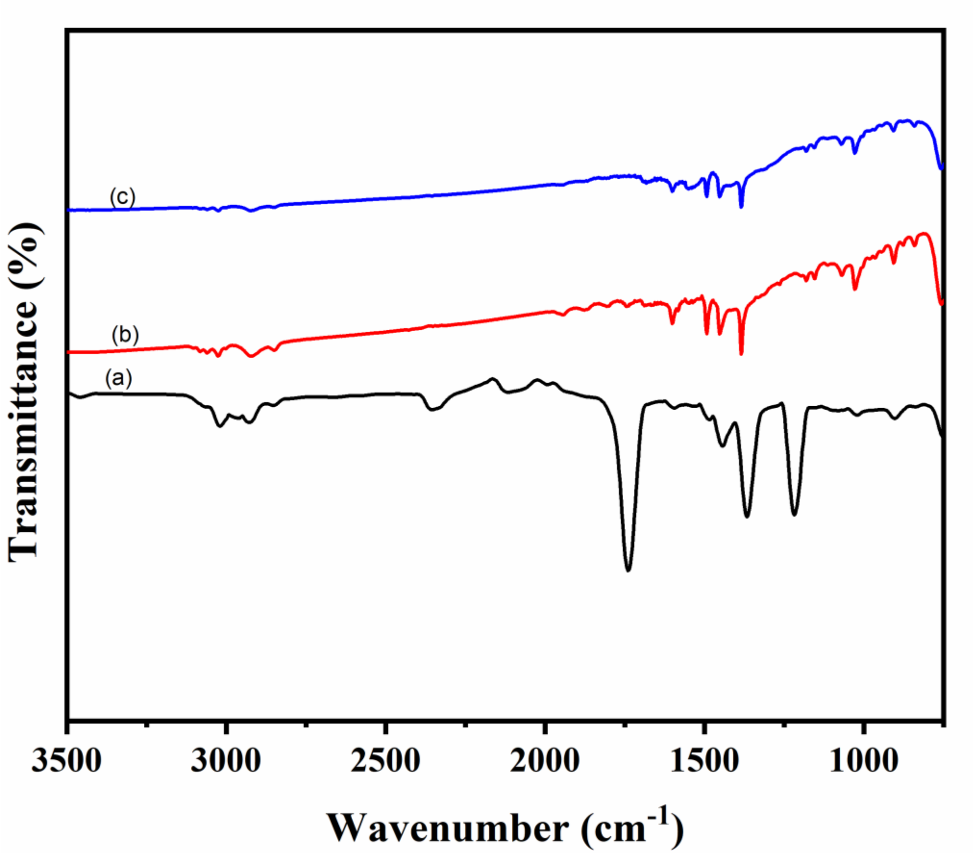
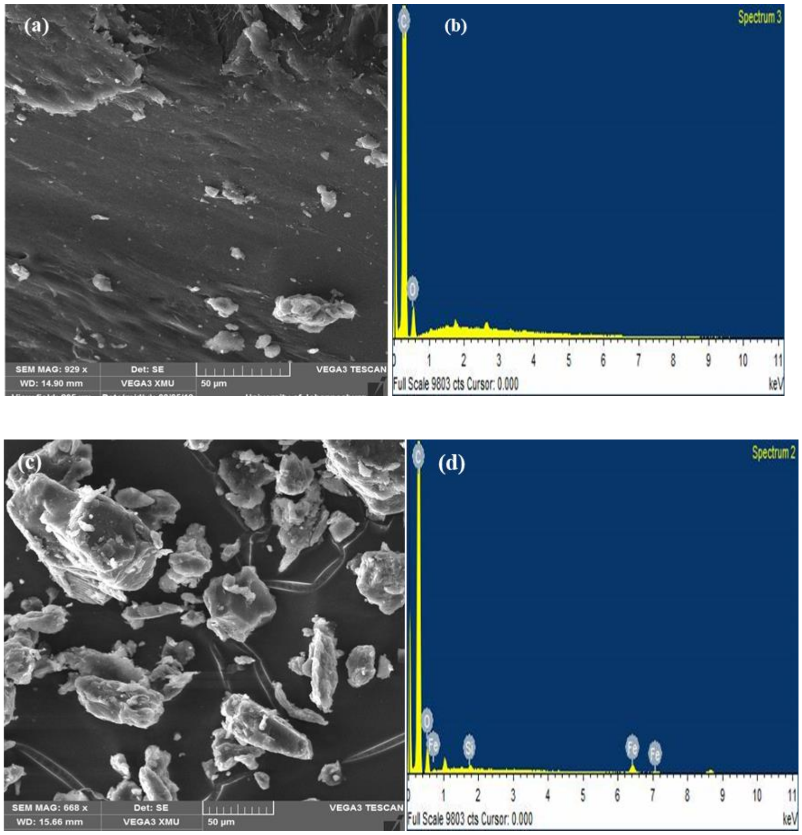


Figure 4: FTIR for a) rEPS; b) Fe2O3 NCs and c) ZnO NCs.

3.4. Scanning electron microscopy (SEM) and Energy Dispersive X-Ray (EDX)

The morphology and elemental compositions of rEPS (control), hybrid Fe_2O_3 NCs and ZnO NCs were studied using SEM images and EDX spectra as shown in (**Fig. 5a-f**). **Fig. 5a** showed the SEM image of the rEPS revealing a smooth-like particle edifice. **Fig. 5b** displayed the presence of oxygen and carbon and peaks were noticed at around 0.5 keV for C and O. **Fig. 5c-d** revealed the SEM image and EDX spectra for Fe_2O_3 NCs. **Fig. 5c** showed globular aggregates in micron dimensions and the aggregates were almost the same throughout uniform particle dimensions. **Fig. 5d** confirmed the presence of iron (Fe), oxygen (O), carbon (C), and some traces of silicon (Si) in the Fe_2O_3 NCs. Moreover, peaks were spotted at 0.5 and 6.4 keV for Fe, 0.4 keV for O, and 1.7 keV for Si [37]. For the ZnO NCs (**Fig. 5e-f),** the SEM image (**Fig. 5e**) confirmed cubical-shaped NCs in which the NCs demonstrated certain clustering/assembling. **Fig. 5f** showed the EDX analysis where the presence of zinc (Zn), carbon (C), oxygen (O) was established. The presence of silicon (Si) might be due to Si wafer. Besides, peaks were detected at 1, 8.6 and 9.5 keV for Zn, 0.5 keV for O [38]. Overall, when **Figure 5a** is compared with **Figure 5c** and **5e**, it was concluded that the incorporation of nanoparticles (NPs) into the polymer matrix influenced the morphologies of the synthesized NCs.



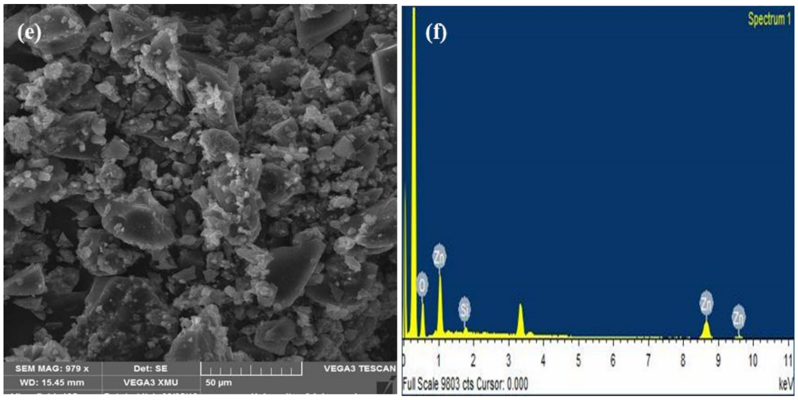


Figure 5: SEM images and EDX spectra for a), b) rEPS; c), d) Fe2O3 NCs and e), f) ZnO NCs.

3.5. Transmission electron microscopy (TEM)

TEM was used to gather information on the incorporation of nanoparticles (NPs) within the polymer matrix and to determine the particle size diameters (PSDs) of the NCs. **Fig. 6a-i** showed the TEM images, SAED micrographs and PSD charts. The TEM image, SAED pattern and PSD charts for rEPS are shown in **Fig. 6a-c**. The TEM image (**Fig. 6a)** displayed an irregular spherical shape. The SAED pattern (**Fig. 6b**) showed broad rings which correspond to amorphous and crystalline phases. It was observed that the diffraction rings corresponding to (100) and (200) agree with the crystal planes of polystyrene. Also, the broad rings are an indication that the material is non nanocrystalline. The average particle size diameter (PSD) (**Fig. 6c**) was evaluated by counting 100 particles from the images taken using ImageJ software. The PSD revealed an interesting result on how the synthesised rEPS was distributed within the synthesised materials for Gaussian fit. **Fig. 6d-f** also presented the TEM, SAED and PSD images for Fe_2O_3 NCs. The TEM image (**Fig. 6d**) was spherical and uniform in shapes [39]. **Fig. 6e** illustrated on the SAED pattern for the Fe_2O_3 NCs. The spots shown on the micrograph are an indication that the materials are nanocrystalline [40-42]. The average particle size was 75 nm (**Fig. 6f**). The TEM image (**Fig. 6g**) for ZnO NCs revealed that the material is spherical in shape and granular in nature. The SAED pattern (**Fig. 6h**) depicted bright spots which agree with the hexagonal wurtzite of ZnO NCs [43, 44] and the spots are also an indication that the materials are nanocrystalline. Its dimension is 58 nm (**Fig. 6i**). These results can be combined with X-ray diffraction (XRD) to evaluate the efficiency of intercalation of the polymer "layers" with the NPs. The average PSD, standard deviations and the polydispersity of the NCs are summarized in **Table 1**.

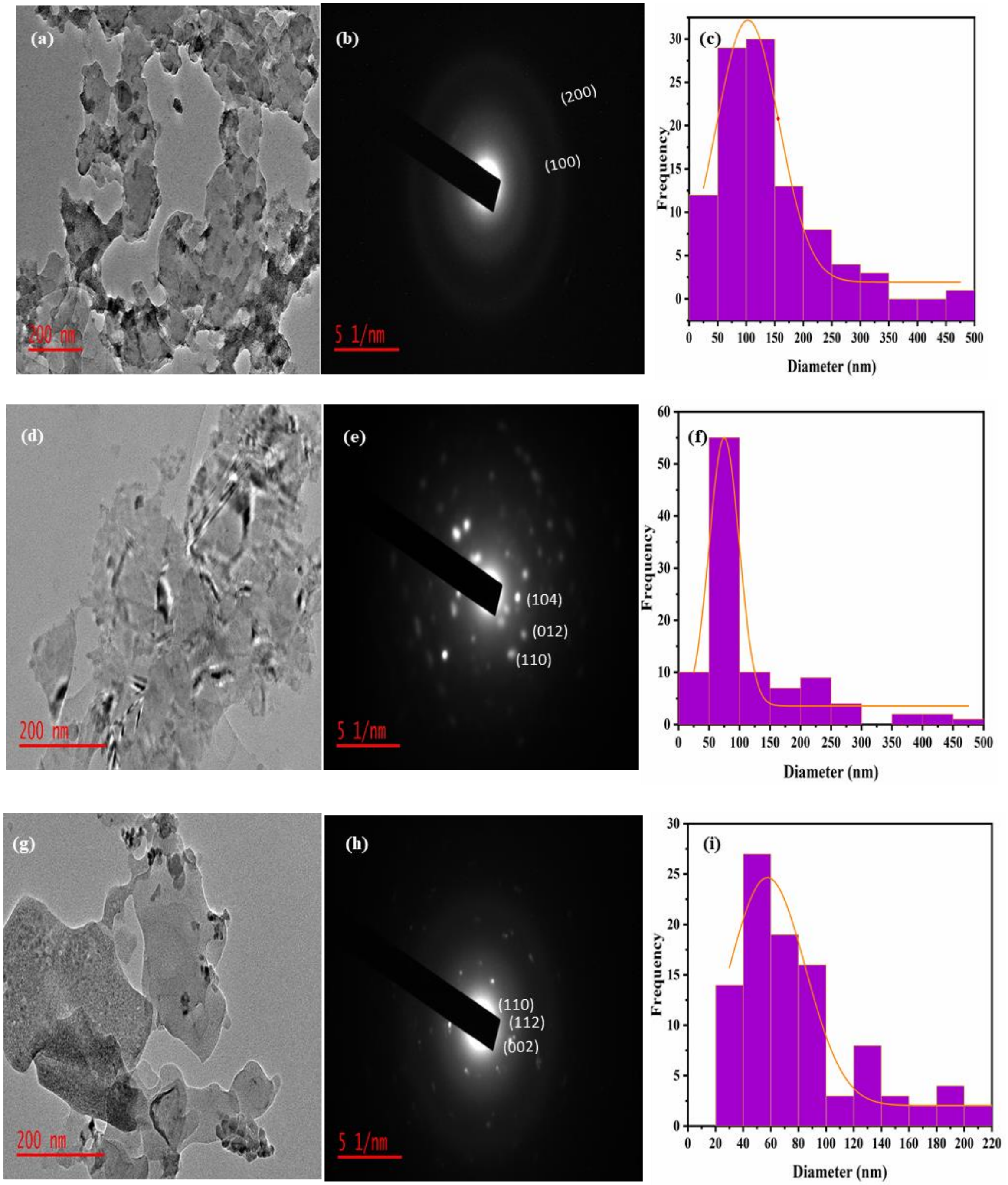


Figure 6: TEM images, SAED pattern and PSD for a), b), c) rEPS; d), e), f) Fe2O3 NCs and g), h), i) ZnO NCs.

Table 1: Average particle size diameters of the synthesised nanocomposites.

Sample name	Average particle diameters (nm)	Standard deviation (nm)	Polydispersity (%)
rEPS	103 ± 4.11	64 ± 5.64	62
Fe_2O_3 NCs	75 ± 4.37	29 ± 2.83	38
ZnO NCs	58 ± 3.55	33 ± 5.01	56

3.6.Thermogravimetric analysis (TGA)

TGA was used to determine the influence of the introduction of NPs into polymer matrix and the thermal stability of the polymers. The TGA and first derivative curves for the rEPS and the NCs are shown in **Fig. 7**. **Fig. 7a** showed the TGA and first derivative curves for rEPS (control) having weight loss from 330 ℃ from the TGA. This might be due to loss of water adsorbed. The next stage of degradation occurred between 330 ℃ and 450 ℃ which could be attributed to the thermal degradation of polystyrene. The first derivative curve has a peak at 480 ℃ (**Table 2**). The degradation on Fe_2O_3 NCs commenced at around 170 ℃ and showed significant weight losses up to 346 ℃ and it continued. The final stage of the degradation was from 450 ℃ and above which might be due to the decomposition of Fe_2O_3 NCs into residues (**Fig. 7b)**. The first derivative curve of the Fe_2O_3 NCs was also shown in **Fig. 7b**. **Fig. 7c** showed the degradation on ZnO NCs which started at around 268 ℃ and the peaks of its first derivative curve. The results of all the analysis are summarized in **Table 2**. It was observed that the presence of NPs in the polymer matrix increase the degradation temperature. It was therefore concluded that the incorporation of NPs into the polymer composites enhanced the thermal stability of the NCs.

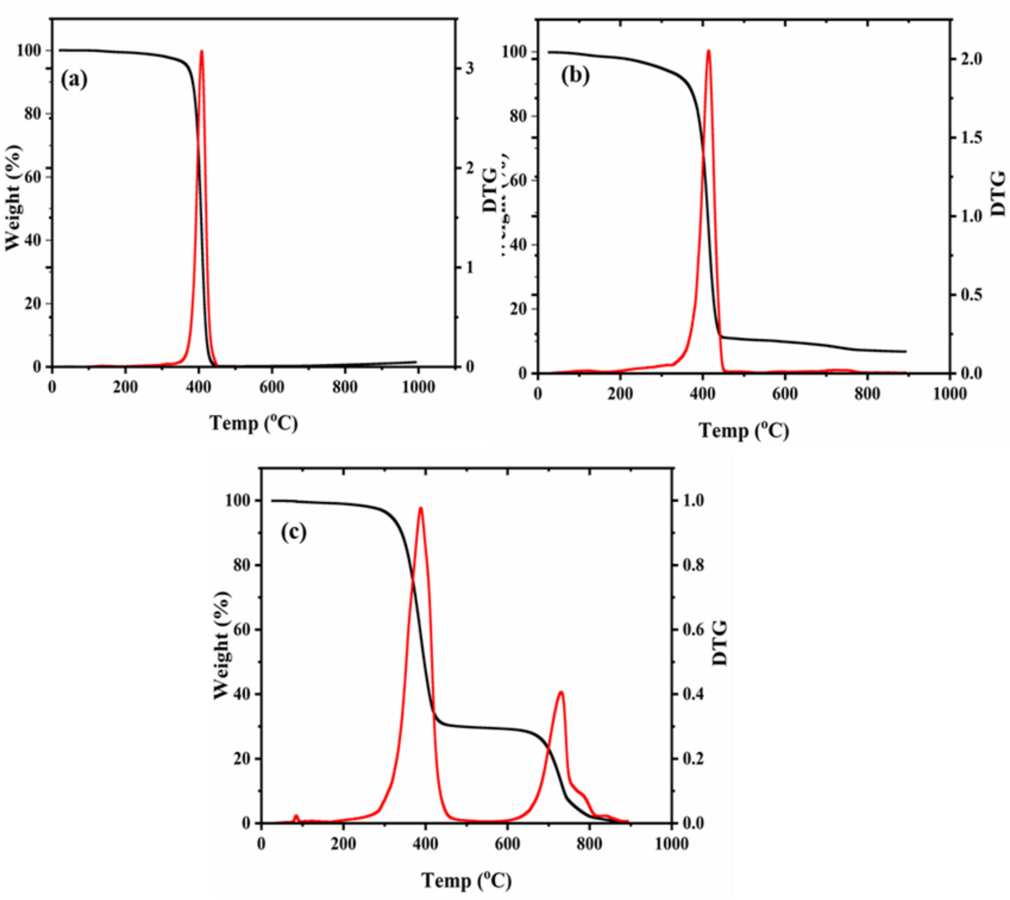


Figure 7: TGA spectra and first derivative curves for a) rEPS; b) Fe2O3 NCs and c) ZnO NCs.

Table 2: TGA results for the synthesised nanocomposites.

Sample	Characteristic temperatures from TGA scans		1st derivative	
	Ti/^{o}C	Tf/^{o}C	T/^{o}C	Inorganic residues (%)
rEPS	335	440	480	0.3
Fe_2O_3 NCs	206	346/444/892	415	11
ZnO NCs	285	430/661/883	387/728	30

3.7.Nanoindentation analysis

The mechanical characterization of materials is extremely challenging to evaluate because of the prevalent upshot of the triggering substrate [45]. Nanoindentation technique can be utilized for the examination of the mechanical characteristics (such as load-displacement curves, displacement-time curve, nanohardness, elastic modulus etc.) of materials. In this study, nanoindentation was used to study the load-displacement curve, nanohardness and elastic modulus of the synthesized NCs.

3.7.1. Load-displacement curves of the synthesized hybrid nanocomposites

The load-displacement tests carried out on Fe_2O_3 NCs, ZnO NCs and rEPS composite under varying indentation loads of 20 mN, 50 mN and 100 mN are represented in **Fig. 8**. Each nanoindentation test on the samples under the loads were carried out 5 repeated times to arrive at an average value (**Fig. 8a-c)**. In **Fig. 8a**, a smaller load of 20 mN was applied on the samples, and as the indenter progresses from 0 to 3 nm, the indentation depth resides between 0.5 and 1.2 nm for all the materials. Meanwhile, Fe_2O_3 NCs displayed the highest resistance to plastic deformation under the 20 mN indentation load with an indentation depth of 0.5 nm and rEPS experienced the maximum plastic deformation with a depth value of about 1.2 nm. Moreover, a higher load of 50 mN was applied as shown in **Fig. 8b**, and as the indenter progresses from 0 to 8 mN, the indentation depth resides between 1.2 and 1.8 nm for all the materials. Similarly, Fe_2O_3 NCs exhibited the greatest resistance to plastic deformation under the 50 mN indentation load with an indentation depth of 1.2 nm and rEPS underwent the maximum plastic deformation with a depth value of around 1.8 nm. In **Fig. 8c**, a much higher load of 100 mN was applied, and as the indenter progresses from 0 to 7 nm, the load values also increase while the indentation depth resides between 1.5 and 3.8 nm for all the materials. Moreover, Fe_2O_3 NCs demonstrated the grandest resistance to plastic deformation under the 100 mN indentation load with an indentation depth of about 1.5 nm and rEPS undergone the highest plastic deformation with a depth value of around 3.8 nm. It was observed that the 100 mN load affords a higher load at a given depth, with a slightly different load-unloading characteristic different from the 20 mN load [46]. The NCs and rEPS composite subjected to 20 mN demonstrated the least deformation during load and unloading while at 100 mN, the materials experienced huge plastic deformation resulting from the larger load. Hence, it was concluded that Fe_2O_3 NCs exhibited the greatest resistance to plastic deformation under all the applied loads resulting from the strengthening mechanisms and precipitation hardening from the Fe_2O_3 [47].

Furthermore, the reduction of indentation depth with the rise in hardness corresponds with the fact that hardness rises with an upsurge in weight percent of Fe_2O_3 NCs. A parallel fashion with respect to values of hardness was also spotted in the case of the ZnO NCs. The lesser displacement is ascribed to the greater resistance presented by the matrix combined with firm Fe_2O_3 NCs and ZnO NCs to the indenter [48]. Additionally, the load-displacement curves illustrated an elastic-plastic deformation characteristic and it was observed that rEPS (control) revealed largest penetration depth at every indentation load [29]. This, therefore, suggested that the inclusion of nanoparticles (NPs) in the polymer matrix helped in enhancing the resistance of the NCs to plastic deformation at some point in indentation tests. Hence, this indicates an enhancement of hardness and stiffness which developed due to load transfer between the polymer matrix to the reinforcement.

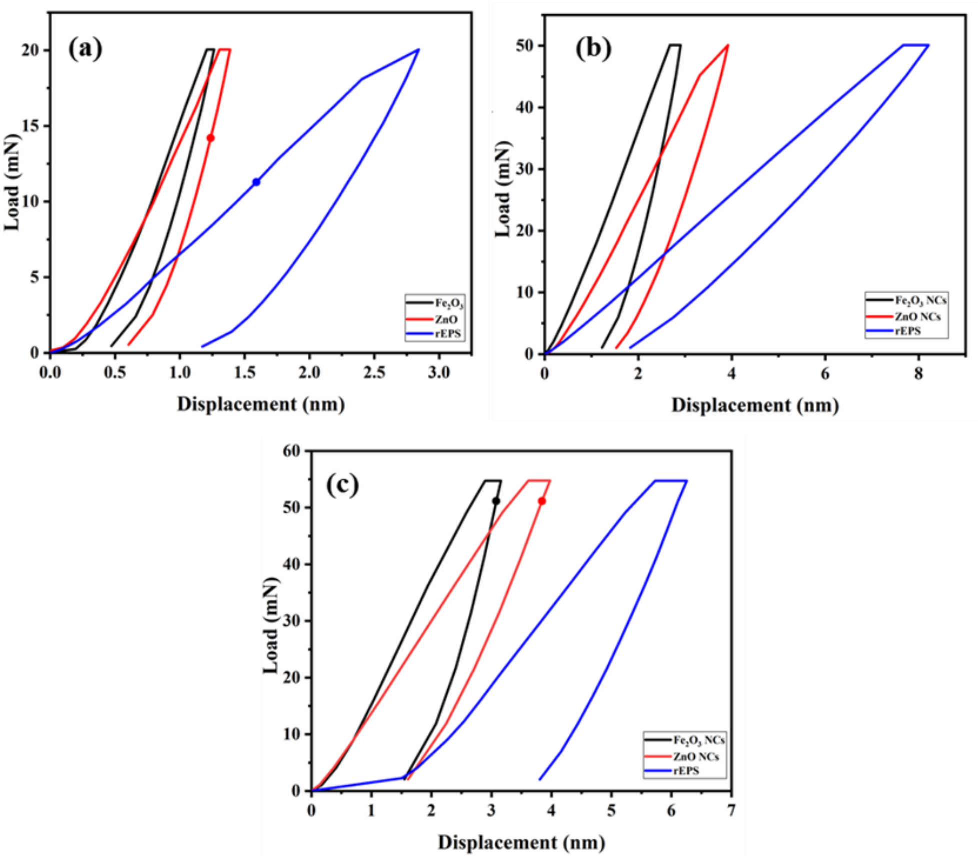


Figure 8: Load-displacement curves for Fe2O3 NCs, ZnO NCs and rEPS under indentation loads of (a) 20 mN, (b) 50 mN and (c) 100 mN.

3.7.2. Nanohardness and reduced elastic modulus of the synthesized hybrid Fe_2O_3 NCs, ZnO NCs and rEPS composite

The nanohardness and elastic modulus of the synthesized hybrid Fe_2O_3 NCs, ZnO NCs and rEPS subjected to indentation load of 20 mN, 50 mN and 100 mN are shown in **Fig. 9**. It was examined that the nanohardness decreases with an increase in load (**Fig. 9a**). At the applied load of 20 mN, Fe_2O_3 NCs have the best hardness values with about 1.2 GPa, at 50 mN, the hardness value stood at 0.65 GPa and at 100 nm, the hardness was almost 0.40 GPa. This is followed by ZnO NCs with hardness values of about 0.75 GPa at 20 mN, around 0.3 GPa at 50 mN and about 0.25 GPa at 100 mN load. On the contrary, the rEPS has the least nanohardness values of 0.36 GPa, 0.28 GPa and 0.13 GPa at 20 mN, 50 mN and 100 mN indentation loads respectively. This shows that the inclusion of nanoparticles into polymer matrix remarkably enhanced the nanohardness of the hybrid NCs. The increase in nanohardness values for the NCs could also possibly mean its resistance to plastic deformation which also agrees with the load-displacement curves shown earlier in **Fig. 8a-c**. Similarly, there seems to be a barrier to dislocation motion resulting from the inclusion of the NPs which assisted in the strengthening of the NCs.

In addition, **Fig. 9b** showed similar trend like the nanohardness charts (**Fig. 9a**) with Fe_2O_3 NCs having the best elastic modulus values of 8.20 GPa, 5.60 GPa and 3.20 GPa at 20 mN, 50 mN and 100 mN indentation load respectively, and followed by the ZnO NCs with 7.00 GPa, 2.50 GPa and 1.60 GPa for 20 mN, 50 mN and 100 mN indentation loads respectively. In contrast, the rEPS has the lowest reduced modulus of 1.90 GPa, 1.50 GPa and 1.10 GPa in comparison with the NCs under the same indentation loads of 20 mN, 50 mN and 100 mN respectively. These results showed that the NCs elastically resist linear compression from the indenter. It was concluded that the inclusion of NPs in the polymer matrix to develop the NCs has improved the stiffness effect of the synthesized NCs. The enhancement in mechanical properties (such as nanohardness and elastic modulus) observed in the hybrid NCs can be attributed to the inclusion of NPs in the polymer composites [49].

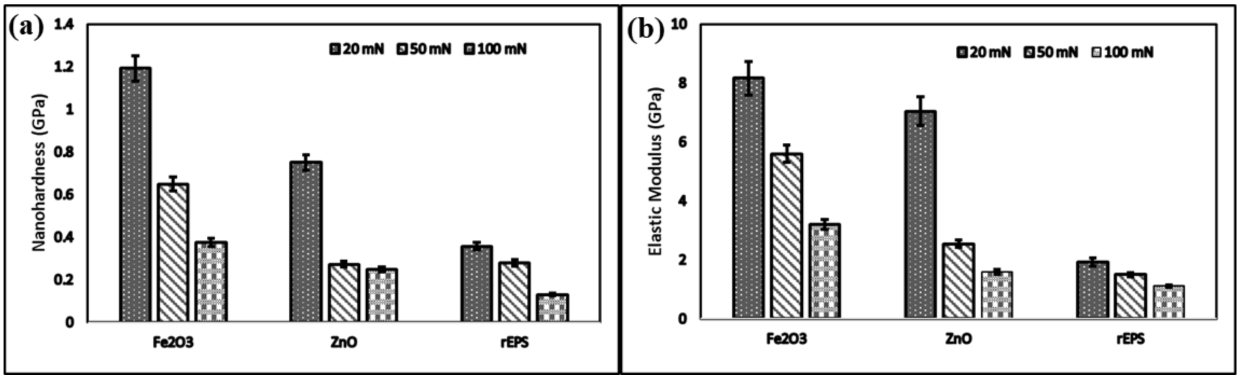


Figure 9: Nanohardness (a) and reduced modulus (b) of Fe2O3 NCs, ZnO NCs and rEPS composite under indentation loads of 20 mN, 50 mN and 100 mN respectively.

3.7.3. Elastic strain recovery and anti-wear resistance

The elastic strain recovery and anti-wear resistance for Fe$_2$O$_3$ NCs, ZnO NCs and rEPS composite were obtained from the nanohardness (H) and reduced elastic modulus (Er) data of the synthesised nanocomposites. As regards elastic behaviour of the materials, the ratio of hardness to elastic modulus (H/Er) is the same as 'elastic strain to fracture'. Similarly, the ratio of the cube of hardness to square of elastic modulus (H^3/Er^2) is the same as the anti-wear resistance. The anti-wear resistance is crucial to the evaluation of the strength of material resistance to plastic deformation [50, 51]. These are generally acceptable means for the evaluation of elastic behaviour of materials. **Fig. 10** showed the results of the analysis where Fe$_2$O$_3$ NCs have the best elastic strain recovery with 0.18 GPa at 20 mN, 0.15 GPa at 50 mN and 0.11 GPa at 100 mN (**Fig. 10a**). Besides, the Fe$_2$O$_3$ NCs has the best anti-wear resistance of 0.02 GPa at 20 mN, 0.01 GPa at 50 mN and 0.0078 GPa at 100 mN (**Fig. 10b**). This is followed by ZnO NCs while rEPS has the least elastic strain recovery and anti-wear resistance. Hence, it was concluded that the inclusion of nanoparticles in the polymer matrix leads to the enhancement of elastic recovery and the sliding wear resistance of the nanocomposites. A recent study has shown that the strength of a material is relative to its hardness and a material with higher hardness retains a higher strength [51]. It was therefore observed that the elastic strain recovery and the anti-wear resistance followed the same trends as the nanohardness and the elastic modulus of the nanocomposites.

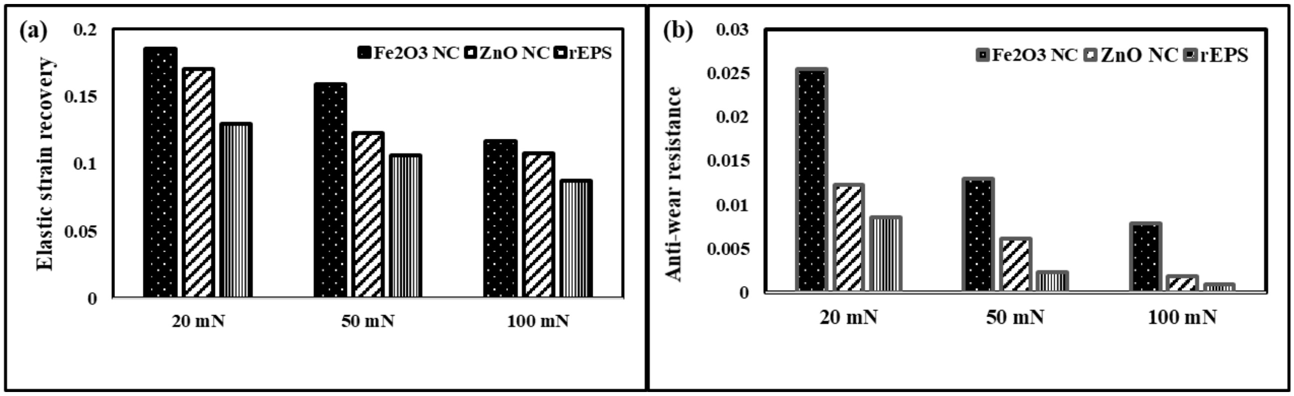


Figure 10: Elastic strain recovery (a) and anti-wear resistance (b) of Fe2O3 NCs, ZnO NCs and rEPS composite under indentation loads of 20 mN, 50 mN and 100 mN respectively.

4. Conclusion

In this study, a simple solvothermal process was utilized to prepare Fe_2O_3 NCs and ZnO NCs. The solvothermal method is cost-effective and environmentally friendly which makes it feasible for commercial scale application when compared to other methods like sol-gel, melt blending, in-situ polymerization, solution blending, direct compounding and melt intercalation. Because of the useful superparamagnetic of Fe_2O_3 NC, it was predicted that they will find applications in drug delivery and magnetic data storage. Also, due to the useful antibacterial and antimicrobial activities of the hybridized ZnO NCs regarding pathogens, they are predicted to be suitable for applications in water treatment and domestic packaging. The XRD images displayed increase in the degree of crystallinity because of the inclusion of the NPs in polymer composites. FTIR revealed that the presence of NPs in the composites did not affect the functional groups. The TEM images showed some spherical and granular shapes and particles of high polydispersity and SAED pattern showed materials are nanocrystalline. The TGA and DTG showed that incorporation of NPs in the polymer matrix increases the degradation temperature. The results of the nanoindentation studies showed that the mechanical properties of the hybridized NCs were enhanced compared to the rEPS.

5. Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declaration of competing interest

The authors declared that there is no Conflict of Interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inoche.2019.107704.

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CHAPTER FOUR

DISCUSSIONS ON ISSUES RAISED BY THE ARTICLES

4.1. The concept of the thesis

The main idea of this present study is directed towards the utilization of recycled plastic materials for the development of value-added materials for varied applications and thereby reducing environmental and health issues associated with improper disposal of PW and ultimately solving environmental problems and health issues experienced by the public. This thesis agrees with the viewpoint that describes a doctoral thesis as a document designed to solve problems via scientific findings which offer solutions to certain research questions. This thesis sought solutions to the challenges of plastic waste management in sub-Saharan Africa through the development of hybrid nanocomposites from polystyrene waste using solvothermal synthesis technique.

This Chapter is dedicated to the detailed discussion of each of the articles developed from the results of the findings of this study and their interrelationship as they convincingly realized the outlined goals of this study. A summary of the rationale of each article was given. Moreover, the contributions to knowledge of each article were summarized. Moreover, arguments with respect to the novelty and impact of this study to prevailing knowledge on the utilization of recycled polymer for the development of value-added materials were outlined.

4.2 Argument for research originality and contributions to knowledge

The primary of objective of this study as outlined in **Chapter One** of this thesis is to develop value-added materials (nanocomposites) from recycled polystyrene for different applications. Owing to the originality of the study, it becomes very crucial to evaluate the mechanical and thermal properties of the developed composite materials. Mechanical property is usually a universal expression used to estimate the mechanical strength and ductility of materials. It provides information such as the amount of load a material can withstand before a tragic failure occurs. Similarly, the thermal properties provide information on thermal stability or processing conditions of certain samples comparative to samples used as control which then allowed thermal analysis to be used for quality assurance. Moreover, information on the chemical compositions, crystallinity, chemical structures, morphology, particle size diameters; pore size, pore volume and surface area; molecular weight distribution and chemical shifts of the synthesised recycled polystyrene, synthesised nanocomposites and the neat polystyrene wastes were all outlined. The results of the findings of this study are described in the journal articles produced. There was a critical discussion on the key issues arising from the articles as they help in accomplishing the goals of this study.

4.2.1. Issues raised from the review paper on plastic waste management

In **Paper 1**, an overview of earlier studies on plastic waste generation and management in Africa and on a global scale were studied. The study presented existing information on the problems connected with plastic waste management globally and, in sub-Saharan Africa. It was discovered from the study that public health is threatened due to poor waste disposal. Besides, the natural environment is impacted negatively due to poor plastic waste disposal. These challenges all originate from the anthropogenic activities of man whereas, many people are unaware of the damaging impact of their activities on other fellow human being and the ecosystem. The anthropogenic activities include, excessive waste generation, frequent extraction of fossil fuels for the manufacture of plastics, littering and illegal dumping of municipal solid wastes; and land, air and water pollution. Furthermore, it was inferred that many factors also contribute to plastic waste management issues, amongst which include, infrequent collection of wastes/low service coverage in rural areas and some parts of urban centers, influx of economic migrants to cities, industrial and economic growth, changes in consumption pattern and high standard of living. Hence, when waste plastics are properly managed, several benefits ensued. These benefits could be economic and environmental benefits. The economic benefits are, reduction/cost saving for the construction of new landfill facilities, incentives derives around wastes by the populace, job creations around wastes, source of revenue to the government while the environmental benefits include, minimization of impact on the environment via the reduction in the use of fossil fuel for plastic production, reduction in global warming, minimization of public health impairment and ultimately, emerging of greener cities. The review also revealed the several promising mitigating measures to address plastic waste problems and the need for public participation and evaluation of their opinions vis-à-vis plastic waste management. While several studies have been carried out on plastic waste management globally, studies on this subject in the sub-Saharan Africa are very limited. **Paper 2** is an annex to the **Paper 1**. It is a Book Section and focused on the potential innovative technique to develop hybrid nanocomposites from recycled polystyrene using solvothermal technique.

4.2.2. Waste education, public participation and opinions

Paper 3 focused on the assessment of public opinion and their participation in a sustainable solid waste management. In this research, the students of the University of Johannesburg, South Africa were the study samples. About 3500 students were interviewed via survey questionnaire but only 2340 responses were received. The main goal for the choice of these students was to educate them first on the need to support and participate in a recycling program for a sustainable environment and a sustainable future. It was believed that since the students have had some levels of exposures over time, they would be good instruments to disseminate the messages on recycling to their immediate families, their communities and the nation at large. In this way, the level of awareness of the public can be assessed using the opinion of the students as a yardstick since each of these students belongs to a family, a community and a province in South Africa and some nations of Africa. It was deduced from the study that many members of the public were not properly enlightened on waste management matters since many of the students were not conversant with environmental issues. The study showed that only about 30% of the respondents have heard about recycling, however, 80% are willing to support the recycling programs. Moreover, a statistical tool known as logistic model was utilized to envisage the potentials for support. Based on the results of the analysis, it was observed that a good number of the respondents were willing to support the recycling programs.

It was concluded that this article provided a basis for the introduction and implementation of waste education in schools, communities and in the sub-Sahara Africa nations. Waste education has been a subject of concern which local government/municipal authorities have been finding it difficult to introduce. Several stakeholders meeting have been held across South Africa and one of the highlights of such workshops is introduction of waste education in schools and communities but hitherto, it is yet to be implemented. This makes studies of these kinds very scanty in low-income countries; hence, this present study becomes a hot subject aimed at addressing/curbing the excesses of the populace with respect to municipal solid waste generation particularly in Africa.

4.2.3. Compositional, morphological, structural, thermal and mechanical properties connected with the inclusion of nanoparticles in the polymer matrix

Papers 4 and 5 presented on the effect of the inclusion of nanoparticles in the polymer matrix for the enhancement of the properties of polymers.

Paper 4 focused on the compositional, morphological, structural, thermal and adsorption-desorption isotherms of the synthesised nanocomposites; and the structural evidences and molecular weight distribution of the neat/unprocessed polymers. The compositional characterizations include, XPS, XRD and FTIR. The XPS gives information on the elemental compositions, XRD provides data on the degree of crystallinity and FTIR presents detailed info on the chemical structure and functional groups of the hybrid organic-inorganic nanocomposites. The SEM presents information on the morphologies of the nanocomposites. The structural analysis includes, TEM and DLS which offer information on shapes and particle size diameter of the nanocomposites, evidence of homogenous dispersion of nanoparticles within the polymer matrix. The thermal characterization includes, TGA and DSC where TGA gives detailed information on the thermal stability of the materials and DSC provides information on the phase changes of the nanocomposites due to the incorporation of nanoparticles into the polymer matrix. The BET presents information on the surface area, pore size and pore volume of the synthesised hybrid materials. The NMR and GPC give detailed information on the structural evidence via ^{1}H-NMR and the molecular weight distribution of the neat/melt processed polymer and rPS (control)/melt processed rPS respectively. Based on the results, it was observed that the inclusion of nanoparticles into the polymer matrix result in the enhancement of the properties of the nanocomposites. Moreover, for the NMR, it was observed that there was no chemical shift in the polymer and the polymers were of aromatic rings and their signals were all doublets which is an indication that a hydrogen atom is attached to two non-equivalent hydrogen atoms and the GPC showed there were no significant changes in the structure of the polymers.

4.2.4. Integrity evaluation of the synthesised nanocomposites via nanoindentation studies of mechanical

Paper 5 centred on the mechanical strength of the hybrid nanocomposites using nanoindentation techniques. The purpose of the nanoindentation testing was to evaluate mechanical properties such as nanohardness, nano elasticity, elastic strain recovery and anti-wear resistance. The hardness and elastic modulus of materials often vary depending on the thickness of coating or materials used for the coating of samples. The elastic strain and anti-wear resistance were obtained from the ratio of hardness to elastic modulus (such as H/Er and H^3/Er^2 respectively). Apart from the evaluation of the mechanical strength, **Paper 5** also examined XRD, FTIR, SEM, EDX, TEM, SAED and TGA. The results obtained from all the analysis likewise confirmed the inclusion of nanoparticles into the polymer matrix for the improvement of properties. The EDX provides information on the elemental compositions of the synthesised nanocomposites. The SAED provides information on the nanocrystallinity and non-nanocrystallinity nature of synthesised materials. Of the three materials (Fe_2O_3 NC, ZnO NC and rEPS) produced in this study, Fe_2O_3 NC and ZnO NC showed features of nanocrystalline which also substantiated that the inclusion of nanoparticles in the polymer matrix is a medium to the enhancement of properties of the synthesised nanocomposites. The results from the mechanical characterization presented load-displacement curve, nanohardness and reduced modulus, elastic strain recovery and anti-wear resistance. For the load-displacement curve, Fe_2O_3 NC showed the highest resistance to plastic deformation under indentation loads and followed by ZnO NC. Equally, the rEPS (control) showed the greatest penetration depth at each indentation load which validated the earlier stands that the introduction of nanoparticles into polymer matrix leads to the enhancement of resistance to plastic deformation.

For the nanohardness and elastic modulus of the hybrid Fe_2O_3 NCs, ZnO NCs and rEPS composite, it was observed, Fe_2O_3 NCs have the best hardness. This is similarly followed by ZnO NCs. The rEPS showed the least nanohardness indentation loads. These results also corroborated that the inclusion of nanoparticles into polymer matrix outstandingly improved the nanohardness of the materials. Similarly, Fe_2O_3 NCs exhibited the best elastic modulus and followed by the ZnO NCs. Here, the rEPS showed the lowest reduced modulus in comparison with the NCs under the same indentation loads separately. These results showed that the NCs elastically resist linear compression from the indenter. It was concluded that the inclusion of NPs in the polymer matrix to develop the NCs has improved the stiffness effect of the synthesized NCs. Furthermore, the elastic strain recovery and anti-wear resistance of the synthesised nanocomposites displayed similar behaviour. In this case, Fe_2O_3 NCs also have the best elastic strain recovery of 0.18 GPa at 20 mN, 0.15 GPa at 50 mN and 0.11 GPa at 100 mN. Besides, the Fe_2O_3 NCs has the best anti-wear resistance of 0.02 GPa at 20 mN, 0.01 GPa at 50 mN and 0.0078 GPa at 100 mN. This is followed by ZnO NCs while rEPS has the least elastic strain recovery and anti-wear resistance. Hence, it was concluded that the inclusion of nanoparticles in the polymer matrix leads to the enhancement of elastic recovery and the sliding wear resistance of the nanocomposites.

4.3. Conclusions

This present study began with the overview of the issues associated with plastic waste generation and management in low-income countries. Attitudes and behaviours of the public, their awareness and opinions with regards to sustainable solid waste management and recycling were evaluated. Hybrid nanocomposites were developed from recycled polystyrene as a way of recycling waste plastic via chemical recycling method (solvothermal technique), thereby lessening the proliferation of plastic wastes at the landfills and in the environment, protecting public health and the environment from pollution and other negative impacts. The effect of inclusion of nanoparticles into the polymer matrix were evaluated using different characterisation techniques such as the compositional, structural, thermal and mechanical properties of the synthesised hybrid nanocomposites. The subsequent inferences were obtained:

1. The issues associated with plastic waste generation and management in sub-Sahara Africa could be surmounted when circular economy is put in place. In this way, all the plastic wastes generated would be sent back into the production processes for the development of secondary materials for varied applications. When this occurs, jobs would be generated around plastic wastes for the unemployed youths, burden on fossil fuel would be minimized, raw materials would be available, impact on public health and the environment would be forestalled, alternative source of revenue to government would be provided, costs on importation of resins will be decreased in that way creating prospects for the local industries (small and medium scale enterprises, SMEs) to grow; and along these lines, the continent of Africa will begin to move towards sustainability.

2. The level of awareness of people with regards to waste management and recycling is still at an infant stage in low-income countries. Many of the respondents were ready to support recycling of municipal solid wastes via participation in source separation. Hence, based on the outcome of the findings, it therefore means that policy makers (e.g. municipal authorities, non-governmental organisations, provincial government and national/federal government) are to pay adequate attentions to the yearnings of the public by providing qualitative and regular education program for them on waste

management and waste handling. Moreover, policy makers are to strengthen the perception of public towards waste management via propagation of information to schools and colleges. Besides, local authorities can as well provide trainings to waste management workers since many of the people being employed to handle waste matters in the developing nations are not having the required expertise for such positions.

3. The strategy used in developing nanocomposites from recycled polystyrene proves useful for the economical repurposing of waste plastics to provide value added materials. The inclusion of nanoparticles within the polymer matrix plays a very important role in the enhancement of the properties of the synthesised nanocomposites. Also, an important feature of the nanocomposites was that the polystyrene matrix was able to stabilize the nanoparticles in solution providing stable dispersions, which could be useful for solution casting or spray coating. In combination with the type of inorganic fillers used in this study, the synthesised nanocomposites may be applicable in photocatalysis.
4. Because of the inclusion of the nanoparticles within the polymer composites, the mechanical strength or integrity of the developed nanocomposites were improved compared to the synthesised polystyrene material. The nanoindentation studies revealed similar trend for all the mechanical testing carried out Fe_2O_3 nanocomposites having the best nanohardness, elasticity, elastic strain recovery and anti-wear resistance.

4.4. Recommendations

This present study authenticated solvothermal technique as a cost-effective and environmentally friendly method of chemical recycling of plastic wastes. It also confirmed that this method has a prospect for commercialization especially when compared to methods like sol-gel, melt blending, in-situ polymerization, solution blending, direct compounding and melt intercalation. The solvothermal technique allowed the hydrophilic nanoparticles to be homogenously dispersed in the hydrophobic polystyrene matrix. This strategy may ultimately prove useful for the economical repurposing of waste plastics to provide value added materials. An important feature of the developed nanocomposites is that the polystyrene matrix can stabilize the nanoparticles in solution thereby providing stable dispersions, which could be useful for solution casting or spray coating. The synthesised hybrid nanocomposites have good nanohardness, excellent modulus of elasticity in addition to excellent elastic strain recovery and anti-wear resistance/plastic deformation. Therefore, owing to the useful antibacterial and antimicrobial activities of the hybridized nanocomposites regarding pathogens, they are predicted to be suitable for applications in photocatalysis/water treatment and domestic packaging.

Appendix A

UNIVERSITY
OF
JOHANNESBURG

10 February 2020

Dear Participants,

This survey is on the “Recycling Attitudes and Behaviour towards Waste Management at the University of Johannesburg (UJ), South Africa”. To this end, we kindly request that you complete the following short questionnaire to assess participation in recycling amongst students and staff and their attitudes towards recycling project. It should take no longer than 15 minutes of your time and to expediate the reading of this survey, please let me quickly point this out that you will keep seeing the word recycling all through this survey. **“*Recycling could be simply described as the conversion of waste into a useful material*”**.

Please do not enter your name or contact details on the questionnaire. It remains anonymous. Kindly submit the completed questionnaire as soon as you have completed it. Your response is of the utmost importance to us.

Should you have any queries or comments regarding this survey, you are welcome to e-mail us at *olusolaolt@gmail.com.*

O.O. Ayeleru

Yours sincerely
University of Johannesburg, South Africa

PLEASE ANSWER THE FOLLOWING QUESTIONS BY CROSSING (×) THE RELEVANT BLOCK OR WRITING DOWN YOUR ANSWER IN THE SPACE PROVIDED.

EXAMPLE of how to complete this questionnaire:
Your gender?
If you are female:

Male	1
Female	[✓ 2]

Section A – Background information

This section of the questionnaire refers to background or biographical information. Although we are aware of the sensitivity of the questions in this section, the information will allow us to compare groups of respondents. Once again, we assure you that your response will remain anonymous. Your co-operation is appreciated.

1. Gender

Male	1
Female	2

2. Age (in complete years)

3. Department at UJ

4. Living condition

Residing alone	1
With roommate (s)/sharing	2
With a partner without children	3
With a partner with children	4
With a parent or family member	5

5. If South African, specify hometown

6. If a Foreign National, specify Country

Section B

This section of the questionnaire explores your recycling attitudes with regards to waste management.

If you are a staff member, please skip question 7, 8 and 9, and continue from question 10.

7. Are you residing at one of the UJ residences?

Yes	1
No	2

8. Which of the UJ residences are you residing?

9. Do you have bin in your residence?

There is bin inside the residence	1
General bin outside the residence	2
No bin at the residence	3

10. What issue (s) do you normally experience with respect to your waste collection in your residence?

Infrequent collection	1
No issue	2
Other, specify,	3

11. Do you know where your collected waste is taken for final disposal?

Yes	1
No	2

12. Have you heard about Recycling?

Yes	1
No	2

13. Would you be willing to support Recycling in UJ and the City of Johannesburg?

Yes	1
No	2

14. Do you currently separate wastes into different components?

Yes	1
No	2

15. If yes, how do you do the separation of food waste from other wastes?

By using separate plastic bags for different wastes	1
By using the separate bins provided by the University	2
Other, specify,	3

If you are a staff member, please skip questions 16, and continue from question 17.

16. If there are UJ employees who clean your room/residence, please choose appropriate option below

They only clean the residence	1
They clean both the residence and the room	2
Other, specify,	3

17. Do students leave papers, plastic bottles etc. lying around on your campus?

Yes	1
No	2

18. Have you seen or heard of people burning waste openly on your campus?

Yes	1
No	2

19. Are there bins positioned at different locations on your campus for collecting wastes?

Yes	1
No	2
I don’t know	3

20. Which day (s) of the week is waste collected from your campus bin? (choose one only)

Mondays	1
Tuesdays	2
Every day of the week	3
Other, specify	4

21. If you are residing off campus, which day of the week is your waste collected? (choose one only)

Mondays	1
Tuesdays	2
Every day of the week	3
Other, specify	4

22. Which Waste Management Agency does UJ use?

Public	1
Private	2
Other, specify	3

23. Which of the following would you regard as environmental problem on your campus? (you can indicate more than one)

Air pollution	1
Unsafe drinking water	2
Insufficient water supply	3
Poor toilet facilities	4
Other, specify	5

24. To what extent do you agree with the following statement?

1-Strongly disagree (SD); 2-disagree (D); 3- neutral (N); 4- agree (A); 5- strongly agree (SA); 6- (DK) I don't know

	SD	D	N	A	SA	DK
Recycling helps to conserve the environment						
Recycling reduces the amount of waste that goes to landfill						
Disposing of waste in a landfill harms the environment						
Recycling can be an alternative source of revenue in the City of Johannesburg						
Complete diversion of waste from landfill is an essential step to resource recovery						
Source separation of waste can lead to a Sustainable City						
Dumping of waste to the landfill sites contributes to climate change						
Proper handling of waste has both social and economic benefits						
Waste reduction and reuse play important role in reducing environmental impact						

If you are a staff member, please skip question 25 and 26, and continue from question 27.

25. Do Students run business in your residences where you live?

Yes	1
No	2

26. If yes, what type of business is it?

Grocery/Provision shop	1
Sweet shop	2
Barbing/Hairdressing salon	3
Selling cooked food	4
Video shop	5
Selling airtime and phone accessories	6
Other, specify	7

27. What is your average spending in a month on?

Food	R
Clothes	R
Transport	R
Airtime	R
Photocopy/printing	R
Beer/cigarette	R
Other, specify	R

Thank you very much for your contribution to this survey. Goodbye.

Appendix B

UNIVERSITY OF JOHANNESBURG

20 February 2020

Dear Participants,

This survey is on the "Recycling Attitudes and Behaviour towards Waste Management at the University of Johannesburg (UJ), South Africa". To this end, we kindly request that you complete the following short questionnaire to assess participation in recycling amongst students and their attitudes towards recycling project. It should take no longer than 15 minutes of your time and to expediate the reading of this survey, please let me quickly point this out that you will keep seeing the word recycling all through this survey. ***"Recycling could be simply described as the conversion of waste into a useful material"***.

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Yours sincerely
University of Johannesburg, South Africa

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3. Department at UJ

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With a partner without children	3
With a partner with children	4
With a parent or family member	5

5. If South African, specify hometown

6. If a Foreign National, specify Country

7. Factors influencing willingness to support recycling

To what extent do you agree with the following statement?

1-Strongly disagree (SD); 2-disagree (D); 3- neutral (N); 4- agree (A); 5- strongly agree (SA); 6- (DK) I don't know

Attitude

	SD	D	N	A	SA	DK
Waste recycling is a good initiative						
I don't think waste recycling has positive impact on the environment						
I try as much as possible to recycle waste						
My feelings towards recycling is positive						
I am not interested in the idea of waste recycling						
Waste recycling is rewarding and beneficial						

Subjective norm

	SD	D	N	A	SA	DK
If more people participate in recycling activities, I will also recycle more waste						
It is expected of me to recycle more waste at UJ in the coming month						
Most of my family members feel waste recycling is a good thing for me to do						
Most people who are closed to me would want me to participate in waste recycling						
Most people who are closed to me feel that I should participate in waste recycling						

Perceived behavioural control

	SD	D	N	A	SA	DK
Many opportunities accrue when I engage in recycling at UJ						
It will be easy for me to engage in recycling at UJ during the coming month						

The University of Johannesburg provides satisfactory resources for recycling						
I know where the University of Johannesburg recycling is, where I can take my waste for recycling						
Recycling of waste is very easy						

Perceived moral obligation

	SD	D	N	A	SA	DK
I feel I should not waste anything if it can be reused						
It will be very wrong of me not to recycle my waste						
Not recycling waste goes against my principles						
Recycling should be our lifestyles						
Recycling looks like the right to do						
Everyone should share the responsibility to recycle waste						

Knowledge

	SD	D	N	A	SA	DK
I would recycle more waste if more information is available to me						
More information on how to recycle waste should be available at the University of Johannesburg						
If I knew what was happening to the recyclables after disposal, I would recycle more often						
There is little information on recycling at the University of Johannesburg						
I know how to recycle my waste						

Inconvenience

	SD	D	N	A	SA	DK
I don’t have time to recycle waste						
Recycling of waste at the University of Johannesburg is inconvenient						
Recycling of waste at the University of Johannesburg is too complicated						
It is inconvenient for me to recycle waste at the University of Johannesburg						
Recycling takes too much space at home						

General information on recycling

	SD	D	N	A	SA	DK
Recycling helps to conserve the environment						
Recycling reduces the amount of waste that goes to landfill						
Disposing of waste in a landfill harms the environment						
Recycling can be an alternative source of revenue in the City of Johannesburg						
Complete diversion of waste from landfill is an essential step to resource recovery						
Source separation of waste can lead to a Sustainable City						

Dumping of waste to the landfill sites contributes to climate change						
Proper handling of waste has both social and economic benefits						
Waste reduction and reuse play important role in reducing environmental impact						

Thank you very much for your contribution to this survey. Goodbye.