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Green Nanotechnology in Nigeria: The Research Landscape, Challenges and Prospects

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Abstract

In this treatise, we examined the activities of researchers of Nigeria descent in the frontier areas of nanoscience and nanotechnology, with a focus on green nanotechnology. The exploration of literature published by scholars were reviewed and compartmentalized on the basis of applications of the nanomaterials. It can be concluded that the level of activities in this area is expanding owing to the emergence of more published works since the beginning of 2010. However, in comparison with research outputs from other developing African countries such as South Africa and Egypt, activities in green nanotechnology are still at low ebb in Nigeria. Issues that are contributory to the slow pace were identified and appropriate solutions in terms of improved funding of education, enactment of national policy on nanotechnology, curriculum development, international cooperation as well as human resource development among others were discussed.

Keywords: Nigeria, developing countries, green nanotechnology, nanobiotechnology, science and technology, technological advancement

1.0 Introduction

One of the most long-lasting legacies that the youth of any country can gain from their leaders is education. Undoubtedly, education is the foundation of societies, and it is through education that cultures are conceptualized and the information is transmitted across generations (Jaja, 2014). It is through education that new concepts and ideas evolve, leading to new frontiers of knowledge that seek to promote growth and development of nations. In recent times, new lines of knowledge have been created in science and technology with outstanding impacts on wealth generation and improved living conditions of man. Among these novel disciplines are information and communication technology, biotechnology, and nanoscience and nanotechnology. While these fields have grown rapidly in the developed nations with commercialized products in the market and integration into daily human activities, a different scenario of near neglect or low activities pervade among developing nations, especially in Africa. At best, most African countries, including Nigeria are consumers of the products of these disciplines that are made by nations of other continents.

The Federal Republic of Nigeria is positioned in the south coast of West Africa and has a population of about 150 million (estimated according to 2006 census) with a literacy level of about 72 % (with variations in regional averages) (Shu'ara, 2010). Her population was projected to have reached 201 million people in 2019 (UNFPA, 2019). Nigeria also had the largest economy in Africa in 2014 with a nominal GDP of about $1 trillion. Being a country that wields commanding power in Africa, considerable influence in global affairs and an emerging global power (Cooper *et al.,* 2007), the expectation is for Nigeria to take a centre stage in educational affairs in West Africa and the African continent at large. However, this aspiration is far from being achieved within the context of developments in science and technology education in Nigeria. In this piece, the focus is on the review of contributions, challenges and prospects in green nanotechnology research and development in the country, with the view of developing a road map for nanotechnology development in Nigeria. The paper also x-rayed the Nigerian educational sector to unravel the problems bedevilling it to attain its set targets and expectations in the training of quality manpower, and to drive growth and development of the nation. Until now, there is no literature that summarizes activities of Nigeria in green nanotechnology.

1.1 Educational institutions in Nigeria

The route of acquisition of knowledge, skills and other capabilities is referred to as education (Jaja, 2014), which is largely grouped into three sectors in Nigeria, namely basic, post-basic or senior secondary and tertiary education. Nevertheless, another system of classification on the basis of horizontal separation is equally available. In this view, early childhood care and development (or pre-primary education) is taken as a component of basic education but is specialized for children younger than school age. Similarly, nomadic education is viewed as an element of basic education, but it is for particular groups of migrants. Adult and non-formal education could also be part of basic education or may go above it, since it can go as high as the post-basic level. Technical or vocational education is a subset inside basic, post-basic and even tertiary education, and teacher education is also a division of tertiary education.

Higher education encompasses all forms of structured educational engagements that take place at an advanced level. These include activities in the colleges of education, monotechnics/polytechnics, and universities. Tertiary education was designed to make outstanding contributions to the development of the nation by training and producing top-notch manpower, developing and impressing right principles for the continued existence of individuals and humanity. It also aims at building the intellectual ability of individuals for the purpose of understanding and values their immediate and other environments. Through higher education, physical and intellectual skills are acquired to empower the citizens on self-reliance and thus become valuable members of the society. Also, education at the various tertiary levels is purposed at promoting and aid learning and rendering of services to the society. It is also expected to promote harmony among the citizens and stimulate national and global interactions (Jaja, 2014).

Amongst institutions that facilitate tertiary education in Nigeria, universities are relied upon to produce high-level manpower in various fields, and the length of studies in universities may range from three (3) to six (6) academic sessions on the basis of the programme. The universities are structured into conventional (offering courses in pure and applied sciences and arts), specialized universities of technology, medicine, agriculture, a full military university, and a quasi-military university. At the moment, there are 171 licensed universities in Nigeria, which included 43 federal, 49 state and 79 private universities (NUC, 2019). Polytechnics are established to train middle-level technical manpower with the graduands awarded national diplomas. There are currently 126 polytechnics in the country; 28 of which are federal government-owned, 43 state governments-owned and 55 owned by private individuals (NBTE, 2019). The colleges of education run three-year programmes with the award of the Nigerian Certificate in Education (NCE). NCE is the least criterion for the teaching profession in Nigeria. There are 21 federal-owned, 43 state-owned, and 25 privately-owned colleges of education (NCCE, 2019). Furthermore, the National Teachers Institute and some polytechnics in Nigeria offer NCE programmes of teacher education. Also, all conventional universities offer courses to earn a Bachelor of Education in various teaching subjects.

The administration of tertiary institutions in the country is based on policies that are laid down by the federal government through her agencies that set guidelines for the establishment, licensing, monitoring, and accreditation of tertiary institutions. Issues that are covered under these guidelines include infrastructure requirements, training facilities and equipment, staff requirements and conditions of service, organogram of administration, curricula for courses, and admission criteria. In the universities, quality assurance is ensured by the National Universities Commission (NUC) as it regulates activities of universities in discharging their duties. The importance of universities for the growth and development of Nigeria has been stressed. It is important to the country to herald the production of skilled citizens; medical practitioners, engineers, agriculturists, teachers amongst others. Through this, the nation can attain self-sufficiency, institutes justice and equity, excellence and healthy society (Jaja, 2014).

1.2 Higher education and development

Higher education being an essential constituent of sustainable human and national development is very important to develop a nation in terms of technology and economy. Bogoro (2015) critically examined the importance of advanced education in Nigeria. As the basis of novel understanding, innovative and inventive idea; tertiary institutions afford the nation with experts in various disciplines with reliable qualifications that bring about innovations and improved competence and productive economy. In achieving this, government had launched schemes that incorporated science and technology (S&T) into the development agenda. Nevertheless, the effects of these schemes have not produced expected results in view of the existing indices of underdevelopment and poverty across board. Therefore, it becomes imperative to re-evaluate the functions and importance of higher institutions in national development and to appraise the prospects of its knowledge-generation and exploitation of outcomes of research activities.

Among the developing nations, Malaysia is a good example that Nigeria can benefit from her experience which has prioritized her research activities around a major agro product of the country; the palm oil. The country established several well-funded research institutions that seek to add value to oil palm, thereby creating wide range of products from the plant. The country has also declared roadmap for science by exploiting her rich natural resources as inputs of industrial expansion and promotion of cutting-edge industries (Bogoro, 2015).

1.3 Attainment of quality in Nigerian University education

According to Jaja (2014), high quality of university education in Nigeria seems to be unachievable for the reason that critical ingredients to achieve quality are inadequate. Some of the problems include low-level employability of university products, inadequate proprietor responsibility, the scope of courses on offer, the capability of teachers in teaching the subjects, strike actions in Nigerian universities and morality of the student. To address these problems, and return the institutions to the path of global competitiveness and vibrancy, a total overhaul of the system is necessary. The reformation must address strategic funding and management (Oduleye, 1985). Other areas of engagement include linkage between the industrial sector and institutions to engender innovative research and improved influx of funds as grants to the institutions. With these provisions, the Nigerian universities should be able match-up with universities in other parts of the world. It has been identified that generally, high spending on education, advanced training, research and development are major incentives that will stimulate national development and growth for the benefits of the society (Bogoro, 2015).

Extensive educational reformations are essential in the country, if Nigeria will keep up with the prospect of playing key roles in the development of the West Africa sub-region. Although, Nigeria still contributes hugely to generation of knowledge in Africa (Lateef *et al.*, 2016a), the modernization of her educational system will have broad significance within West Africa (Moja, 2000). Nigeria is a stabilizing force in the region having spearheaded the restoration of peace in Liberia and Sierra Leone and promote civil rule. It should also be regarded as an educational reference point by many neighbouring countries; however, the country is yet to leverage on these to advance her educational pursuits. While the country had world-class universities up to late ’80s, severe deterioration with negative impact on the quality of graduates has been witnessed since the early ’90s. Therefore, to return the Nigerian institutions to the path of glory for the realization of the potentials of the country, concerted efforts that involve all identifiable stakeholders, development partners, foundations and NGOs should be made to turn around the sector (Moja, 2000).

2.0 Science and technology

Since the third millennium, the world has experienced several cognitive advances in science and technology with improvement in the quality of life (Selim *et al.,* 2015). However, in few cases, the scientific advancement has thrown up new challenges of environmental degradation, poor wellbeing and disorder in the society which can also be resolved scientifically. Certainly, scientific advances have improved civilization and drawn the future closer for the benefits of mankind (Selim *et al.,* 2015). One of such advances is the emergence and development of nanoscience and nanotechnology.

2.1 Nanoscience and nanotechnology

Nanotechnology is an evolution of a pristine multidisciplinary idea of the 21st century that deals with the study of matter at the nanoscale range. It has bridged gaps in materials science and engineering, natural sciences and medicine, through incredible relevance in different sectors. Nanoparticles are the significant parts of this technology that are playing outstanding functions to spread the cutting edge applications of the budding field (Lateef *et al.,* 2018a). Moreover, the scope of nanotechnology involves manipulation of atoms and molecules and their control for the generation and creation of novel materials, nano-based equipment and devices for several applications (Uddin and Chowdhury, 2001). The market value of nanotechnology impacted goods has been projected to reach US$ 1.6 trillion at the end of 2013 (Mohammad *et al.,* 2012). This is so because in developed nations, huge resources have been invested in nanotechnology in view of the prospect of nanotechnology to create a new range of novel products. Investigations in nanotechnology have altered the conventional landscape of practices in engineering, including design, analysis, and production. Thus, its impact poses new challenges to the scientific community in educating and equipping learners with required information and expertise to understand new world of nanotechnology (Ozel and Ozel, 2008).

2.2 Relevance of nanotechnology in the society

Public knowledge and perception of science is low in numerous developing and even the developed parts of the world, although the level of understanding is far better in the developed world. Awareness and understanding of nanoscience and nanotechnology as a subject matter is scanty or far lower in the developing world and that is why it is still indeed called "an emerging field". Nanotechnology encompasses synthesis, design, characterisation, and application of materials, instruments and systems through manipulation of shapes and sizes at nanoscale. Also, a nanomaterial is described as any material whose internal structure or external dimensions exist at the nanoscale, which could demonstrate novel characteristics in comparison with bulk material (Leinonen and Kivisaari, 2010).

Nanoscience and nanotechnology have quite a lot of societal consequences which are beneficial to humans (Rocco and Bainbridge, 2005). The union of nanotechnology with biotechnology and information technology according to Leinonen and Kivisaari (2010) could proffer solutions to many societal problems; for instance healthcare and working capacities of aging population, poverty and inequality (mostly in developing and underdeveloped nations), loss of jobs and poor workplace safety, undesirable exploitation of natural resources, environmental degradation, global warming, detection and treatment of diseases.

The three key nano-technologies of priority at the moment include nano-medicine, nano-energy and nano-environment, and nano-information and communication technology (Bonazzi *et al.,* 2010). The scope of nano-medicine involves nanoimaging, development of nanodevices, novel therapeutics, theranostics, drug delivery systems, clinical, regulatory and toxicological issues, while nano-energy involves solar technologies, hydrogen production, storage and fuel cells, environmental protection, and the generation and distribution of energy through the application of catalysis. Nano-environment encompasses the production of eco-friendly materials such as biodegradable plastics, less toxic rechargeable batteries, and self-cleaning, nano-coated glass. The contamination of available fresh water resources especially due to inappropriate disposal of industrial, agricultural and municipal wastes (Bakare *et al.,* 2003; Adewoye and Lateef, 2004; Lateef, 2004; Lateef and Yekeen, 2006; Lateef *et al.,* 2007) has led to drastic reduction in the quantity of safe water for agriculture and domestic applications (Adewoye *et al.,* 2013). It is possible to enhance the quality of water using nanoparticles-based filters, while pollution detection can be achieved through remote, miniature and nano-based sensors. Nanotechnology in information and communication technologies can improve information processing systems resulting in more potent hardware, large memory-storage capability, faster access, and data conservation during power interruption.

2.3 Nanotechnology in science and technology policy in Nigeria

The Federal Ministry of Science and Technology in Nigeria communicated the Science, Technology and Innovation (ST&I) Policy in 2012 with general objective of building a virile science, technology and innovation capacity and capability required to produce a modern economy, while the specific objectives include, knowledge acquisition, institutional support, innovation, encouragement of diffusion of local technology, development of ST&I database, creating and sustaining dependable mechanisms for funding, initiating and strategizing on bilateral and multilateral cooperation in ST&I. Furthermore, the National Agency for Science and Engineering Infrastructure (NASENI) is an organization that considers nanotechnology as one of the key emerging areas where Nigeria is still lacking and lagging in expertise and proficiency (along with ICT and biotechnology). Therefore, nanotechnology is seen as one of the 'technologies of the future' for Nigeria and should be given priority for research and development (NASENI, 2019).

The national centre for nanotechnology and advanced materials was established by NASENI and it has collaborations with several bodies including the US-Africa Materials Institute, Federal Institute of Industrial Research, the European Union, and Africa Institute of Technology (Tobin and Dingwall, 2010). Also, the authors observed that over the previous ten years, after South Africa, Nigeria has been the second most active country in nanoscience and nanotechnology in the sub-Sahara Africa region based on research publication output. Besides, four main subject matters were identified as being relevant to Nigeria's needs and these include nano-medicine (disease detection and therapy), nano-energy, nano-biotechnology and nano-porous materials. It was also reported that as at 2010, universities in Ibadan and Ife have been the most productive in nanotechnology related research and confirmed the existence of a national initiative on nanotechnology as well as contribution in regional and global activities. Most recently, the federal ministry of science and technology inaugurated a steering committee on nanotechnology development to develop a national policy on nanotechnology (NTA, 2018).

Earlier, Batta *et al.* (2014) investigated the extent to which science and nanoscience have been outlined in three Nigerian newspapers throughout the year 2012; the same year that policy on Science and Technology was revised in the country. It was reported that there was almost nonexistence of nanoscience-related issues in the three newspapers. However, reporting of other science topics existed. The very little area where reports on nanoscience occurred at all, it was outlined as an emerging field. Similarly, news items on socio-economic implications, risk/controversy, or safety/ethics of nanoscience rarely occurred. Thus, it can be concluded that awareness of nanoscience, its applications and implications on the economy among Nigerians is still at infancy. Nevertheless, activities of the research group of the lead author of this article have been disseminated widely in print, electronic and social media which has enlightened a lot of people including students, scholars and policy makers on the scope and importance of nanotechnology (City Mirror News, 2017; City Voice Nigeria, 2018; Daily Independent, 2018; Guardian 2018a, b; LAUTECH News, 2017, 2018; National Insight News, 2018; SCIDEV, 2017; The Business Day, 2018a, b; The Nigerian Tribune, 2017, 2018). Similarly, activities of the research group at the University of Nigeria, Nsukka and at Federal University, Oye-Ekiti on nanotechnology have also been reported in the media (Guardian, 2018c; Vanguard, 2018; The Sun, 2019). However, one key area that can boost the awareness of nanotechnology in Nigeria is by incorporating it in the education curriculum as a major area of science and technology at both secondary school and higher education.

2.4 Incorporation of nanotechnology in education curriculum

Several attempts have been made in the past to reform the existing curricula of science subjects to cope with advances in science and technology (Selim *et al*., 2015). The reorganization was to promote the culture of scientific investigation as a major rationale of science education. The reforms also sought to develop scientific investigation, technological design, critical thoughts, creativity in decision making, and invoking analytical solutions from an individual and collective viewpoint. However, the authors noted that reforms have not yielded expected results in raising younger generations with capacity for vital and ingenious thoughts. It is therefore a challenge to evolve science curricula that would keep learners abreast of the changing societal needs. The finest of science curricula have objectives of training learners to imbibe behaviours, attitudes, skills, and scientific philosophy for the wellbeing of the society (Abul-Ezz, 2004). With regard to nanotechnology, some countries have strived to incorporate issues on the discipline in curricula of related science subjects at high school.

In Egypt, in reaction to the absence of the concepts and understanding of applications of nanotechnology in the curriculum of secondary school Physics, researchers have compared contents of Physics in Egypt with those of other nations (Selim *et al.,* 2015). Through this effort, they formulated a list of 52 concepts in nanotechnology for integration into the secondary-stage Physics curriculum. Similarly, comparative study of engineering curricula of Malaysian universities and those in Australia, UK, USA and Singapore revealed low contents of nanotechnology in curricula of universities in Malaysia at undergraduate level (Mohammad *et al.,* 2012). To ameliorate the inadequacy, the curricula of engineering courses were modified to accommodate electives courses in nanotechnology which enhances early exposure to the discipline among undergraduate students. It was hoped that through this effort, undergraduates can benefit from studying nanotechnology to stimulate their aspiration for further research in nanotechnology, particularly at postgraduate level.

Uddin and Chowdhury (2001) summarized the educational outcomes of a nanotechnology course to stimulate the contributions of graduates to the developments of nanotechnology. These are as follows: the curriculum should be adequate at providing understanding, synthesis, characterization and evaluation of attributes of nanomaterials, manufacturing and processing of nanomaterials, offer capability to invent, analyze and simulate nanostructures and nanodevices, equip students to undertake viable and novel investigations in nanotechnology for applications in human daily lives (Mohammad *et al.,* 2012). In Nigeria however, engineering and science curricula at undergraduate levels lack adequate inclusion of nanotechnology.

3.0 Green nanotechnology

The green nanotechnology approach is a promising area of nanotechnology in which environmentally non-threatening resources such as intact cells, bioactive extracts derived from green plants and animals or metabolites of microorganisms, are utilized in the biofabrication of nanoparticles of metallic origin (Elegbede and Lateef, 2019). Metallic nanoparticles (MeNPs) are renowned for the different types of purposes that include electronics, optics, catalysis, and in the production of nano-devices (Adelere and Lateef, 2016a). The fabrication of MeNPs using the aforementioned environmentally benign materials is termed "green synthesis". The green route is beneficial in comparison with physicochemical techniques because it has been widely shown to be safe, simple, quite reproducible, cost-effective, and often generates more stable materials (Elegbede and Lateef, 2019).

Metallic nanoparticles have been produced using synthetic techniques and these methods include ion exchange, precipitation, sol-gel process, pyrolysis, ionizing radiation, radiolysis, heating technique, laser irradiation and reversed micelles (Ingelsten *et al.,* 2001; Abid *et al.,* 2002; Gamez *et al.,* 2003; Huang and Yang, 2004; Senapati *et al.,* 2005; Braun *et al.,* 2006) with manipulative size and shape. However, most of the chemicals used as reducing agents are toxic, flammable, poses disposal problems as a result of ecological concerns and have poor yield (Mohanpuria *et al.,* 2008; Sharma *et al.,* 2009), with attendant fear for a healthy environment. Consequently, there have been renewed efforts seeking for techniques to synthesize MeNPs and this led to the "green synthetic approach", which involves the utilization of inexpensive eco-friendly bioresources to synthesize MeNPs (Adelere and Lateef, 2016a; Lateef *et al.,* 2018a). Biosynthesis has remained a foremost contributor to the development of nanotechnology steering biofabrication of MeNPs in an environmentally-friendly and benign manner. Additionally, the lack of using unsafe methods and chemicals in synthesis also enlarges the application fronts of nanoparticles synthesized through biosynthesis for biomedical functions as they exhibit improved biocompatibility (Oladipo *et al.,* 2017a). Biological procedure for biofabrication of metallic and metallic oxide nanoparticles of desirable sizes and morphology is the basic interest in strategic areas of nanoscience and has made massive advancement recently. Numerous bioresources such as enzymes, extracts and metabolites of microbes, plants and animals have been exploited to drive biofabrication of MeNPs (Lateef *et al.,* 2015a, b; Lateef and Adeeyo, 2015; Thunugunta *et al.,* 2015; Adelere and Lateef, 2016b; Lateef *et al.,* 2016b, c, d, e; Ojo *et al.,* 2016; Adelere and Lateef, 2019).

The simplicity of one-pot synthesis, through which biomolecules that facilitate the reduction of metal ions and capping of MeNPs are sourced from a sole bioresource, accessibility and variety of biomaterials, in addition to the simple procedure of the synthesis of nanoparticles have greatly contributed to progress being witnessed in the sub-discipline of nanobiotechnology; the fusion of materials and life sciences. One-pot synthesis is easy because the biomaterials being utilized in green nanotechnology are very rich biomolecules for example proteins, phenolics, flavonoids, polysaccharides, vitamins, pigments, alkaloids, and essential oils for the catalytic reduction of metal ions to zero-valent metals under ambient conditions (Oladipo *et al.,* 2017a). In addition, enhanced biocompatibility of biosynthesized nanoparticles has increased their relevance in nanomedicine. Therefore, there is an increasing interest in exploring abundant bioresources of nature to synthesize MeNPs for diverse applications.

The research activities of the academic circle in Nigeria in this important area of science and technology need to be evaluated if Nigeria will keep her status as one of the countries that play major roles in the progress of science and technology in Africa. Therefore, this review was conceptualized for the documentation of research activities in green nanotechnology in the country, with the view of appraising the status of Nigeria in the field, identify the gaps in nanotechnology research and proffer solutions to the challenges, towards developing a roadmap for nanotechnology policy in the country. Until now, there is no literature survey of contributions of Nigeria in green nanotechnology.

4.0 Survey of research activities at Nigerian institutes/universities on green nanotechnology (Table 1)

4.1 Biosynthesis of silver nanoparticles (AgNPs)

Akolade *et al*. (2012) synthesized AgNPs using banana trunk fibres, with plasmon resonance obtained at 420 nm. The AgNPs trapped in banana trunk leading to the formation of a composite displayed prospect of use in the development of banana trunk-based value-added products such as ceramic water purifier, production of egg crates which could promote increased shelf life or protection of eggs. It can also be incorporated in shoe-insole which could inhibit the growth of microbes that inhabit damp shoes and cause offensive smells. Adesuji *et al*. (2013) in a study aimed at using biologically cheap resources for the synthesis of AgNPs investigated ten readily available alcoholic beverages in the nanostructuring of silver. The UV-vis spectrometric studies showed characteristic absorption within 400-450 nm for the samples. The nanoparticles were spherical-shaped, with sizes of 6.5-20 nm. It was therefore concluded that alcoholic beverages are not only meant for consumption, they can also be applied in nanoscience and nanotechnology.

Abubakar *et al*. (2014) synthesized AgNPs using black carrots as the source of phytochemicals reduction, capping and stabilization of the particles, which were averagely 9.46 nm. Dare *et al.* (2015) also reported the kinetic biosynthesis of AgNPs facilitated by plant extracts (*Aframomum melegueta*, *Anacardium occidentale*, *Psidium guajava*, *Ocimum gratissimum*, *Newbouldia laevis*, *Telfairia occidentalis*, *Gangironema latifolium*, *Piper guineense*, *Citrus aurantifolia* (leaf), *Xylopia aethiopica*, *Capsicum chinense*, and *Vernonia amygdalina*) which are about 8-53 nm in size. Elemike *et al*. (2017a) as well reported the use of extract of leaf of *Lasienthra africanum* to synthesize AgNPs. The kinetic studies showed that AgNPs synthesis was affected by the concentration of precursor, pH, temperature, and duration of reaction, which influenced their sizes. Thus, unique particles for desired applications can be fabricated. Sodeinde *et al*. (2016a) biosynthesized AgNPs with extract of *Bassella alba* leaves producing particles of 16-25 nm. Moreover, Akinsiku *et al*. (2015) phytosynthesized AgNPs with the extracts of *Senna occidentalis* and *Canna indica.* Barminas *et al*. (2014) also described an environmentally friendly approach for synthesis of 2-100 nm sized AgNPs by employing extract of *Ageratum conyzoides*.

4.2 Biosynthesis of gold nanoparticles (AuNPs)

Dozie-Nwachukwu *et al*. (2016a) described the phytosynthesis of AuNPs from *Nauclea latifolia* leaf extract and the implications for detection and treatment of cancer were elaborated. Dozie-Nwachukwu *et al*. (2016b) also showed that both whole-cell and cell-free extract of *Serratia marcescens* produced AuNPs via green synthesis. Sodeinde *et al*. (2016a) biosynthesized AuNPs with extract of *Bassella alba* leaves that are of 20-25 nm in size. Sodeinde *et al.* (2016b) equally synthesized AuNPs using the aqueous extract of *Chrysophyllum albidum* for catalysis. Usman *et al.* (2019) investigated the use of oil palm leaf extract to synthesize AuNPs under the influence of radiation. The synthesized AuNPs had a size range of 92.37-112.3 nm.

4.3 Biosynthesis of zinc-and cadmium-selenium nanoparticles

Oluwafemi *et al*. (2010) described a simple "green" synthesis of golden yellow ZnSe nanoparticles using ascorbic acid through a procedure that is reproducible, economical and meets all criteria for green synthesis of nanoparticles and has potentials for medicinal application. At room temperature, Oluwafemi (2009) employed starch in simple, green, and one-pot synthesis of CdSe nanostructures with an evident quantum effect. In another study, Oluwafemi and Adeyemi (2010) biosynthesized ZnSe nanoparticles capped with soluble starch. TEM micrographs revealed well dispersed 2.3-4.2 nm particles that were suggested for wide range applications in luminescence probe, biomedical labelling, catalysis, food and pharmaceutical industry. Furthermore, Oluwafemi and Revaprasadu (2008) reported the environmentally benign production of monodispersed ZnSe and CdSe nanoparticles using starch, cysteine and ascorbic acid. The water-soluble synthesized nanoparticles were observed to be stable on exposure to air and moisture with potential applications in biomedicine.

4.4 Biosynthesis of chromium, nickel, tungsten oxide, palladium and platinum nanoparticles

Mamuru *et al*. (2015) employed leaf extract of *Annona squamosa* to biosynthesize chromium and nickel nanoparticles at neutral pH with SPR at 285 nm. In another study, Mamuru and Jaji (2015) biofabricated nickel nanoparticles using *Moringa oleifera* with prospective applications in catalysis and development of biosensors. Sodeinde *et al*. (2016a) biosynthesized palladium nanoparticles using leaf extract of *Bassella alba* with particles of 10-14 nm. Similarly, Olajire and Adesina (2017) synthesized platinum and Au@platinum nanoparticles with extract of leaf of *Carica papaya* with a size range of 3.94-5.48 nm. The extract of the bark of *Alchornea laxiflora* also yielded the bioformation of platinum nanoparticles that are typically 3.68-8.77 nm (Olajire *et al*., 2017a). The particles desulphurized model oil to remove dibenzothiophene dissolved in n-heptane, with better activity than acetic acid. Similarly, the extract was used synthesize Pt@Cu nanoparticles with a size range of 1.87-2.38 for the desulphurization of model oil (Olajire *et al*., 2017b). Tijani *et al.* (2019) have reported biofabrication of tungsten oxide (WO_3) with the aid of leaf extract of *Spondias mombin* with the study involving the investigation of the effects of pH and calcinations temperature. There were formations of dispersed particles at investigated pH except at the pH of 13.

5.0 Studies on applications of nanoparticles

Several studies have been conducted by researchers in Nigerian institutions on green synthesis of different types of MeNPs using varieties of biomaterials and evaluation of the particles for applications as antimicrobial, antioxidant, larvicidal, desulphurization, dye degradation, anticancer, anticoagulant and thrombolytic agents. Some studies also delved into renewable energy, where nanoparticles have been used to improve the efficiency of solar cells. All these point towards exploitation of nanoparticles in biomedicine, agriculture, environment and energy sectors. These activities are reviewed in the accompanying sections.

5.1 Biomedical, agricultural and environmental applications

5.1.1 Silver nanoparticles (AgNPs)

5.1.1.1 Antimicrobial activities

Elemike *et al*. (2014) biosynthesized AgNPs with the aid of leaf extract of pineapple (*Ananas comosus*). The synthesis was signified by a reddish-brown colour change in aqueous solution. The 12. 4 nm sized spherical biofabricated AgNPs which were homogeneous suppressed the growth of *Streptococcus pneumoniae*, *Escherichia coli, Staphylococcus aureus*, and *Proteus mirabilis*. Johnson *et al.* (2014) examined biosynthesis of AgNPs with the aid of leaf extract of *Sida acuta* and *Artemisia annua*. The AgNPs showed good inhibitory effect on *E. coli, S. aureus* and *Candida albicans*. Ajayi *et al*. (2015) synthesized AgNPs using seed extracts of two medicinally important plants; *Cyperus esculentus* and *Butyrospermum paradoxum*. The AgNPs were active against *Klebsiella pneumoniae*, *Salmonella typhi*, *E. coli*, *S. aureus*, *Pseudomonas aeruginosa, C. albicans*, *Aspergillus niger*, *Penicillium notatum* and *Rhizopus stolonifer*.

Lateef *et al.* (2015a) fabricated spherical AgNPs with crude keratinase synthesized by *Bacillus safensis* LAU 13; a novel keratin-degrading bacterium (Lateef *et al.,* 2015c). Antibacterial potential of the AgNPs was investigated against five clinical strains of *E. coli* with inhibition zones of 8.6 to 12.5 mm. Also, Lateef and Adeeyo (2015) biosynthesized AgNPs using crude laccase of a mutant strain of *Lentinus edodes* which displayed SPR at 430 nm. The walnut-shaped AgNPs with sizes of 50-100 nm displayed effective antibacterial potentials against clinical isolates such as *P. aeruginosa, E. coli* and *K. pneumoniae* with maximum inhibition recorded as 20 mm for *E. coli* strains. In another report, Lateef *et al.* (2015d) described the biosynthesis of AgNPs that had SPR at 419 nm by utilizing the cell-free extract of *B. safensis*. The spherical-shaped particles with sizes of 5-95 nm were active against multidrug-resistant (MDR) strains of *E. coli, S. aureus, Klebsiella granulomatis,* and *P. aeruginosa*. Also, in synergistic studies, AgNPs enhanced the activities of ofloxacin, cefixime, and augmentin to about 142.9 %. Furthermore, the AgNPs was active against deterioration microorganisms in paints; with a total inhibition of microbial growth. Likewise, in anti-candidal activity test, results obtained showed inhibition of *C. albicans* by the synthesized AgNPs with MIC recorded at 40 µg/mL (Lateef *et al.,* 2016e).

Lateef *et al.* (2015e) utilized extracts of seed (SE) and seed shell (SS) of *Cola nitida* to produce AgNPs with SPR of 457.5 and 454.5 nm obtained respectively. TEM micrographs showed that both AgNPs had a spherical shape having sizes 5 to 50 nm. The AgNPs acted against *K. granulomatis, P. aeruginosa,* and *E. coli* with inhibition of 10-32 mm. The SS-AgNPs had better antibacterial activities than SE-AgNPs. Lateef *et al.* (2016d) also described the biomedical applications of AgNPs biosynthesized using cobweb. The particles were spherical-shaped with sizes between 3-50 nm, and active against multidrug-resistant *K. granulomatis, S. aureus*, *P. aeruginosa,* and *E. coli* resulting in zones of inhibition between 10-17 mm. The AgNPs also improved the potencies of ofloxacin, augmentin and cefixime in a mix, and suppressed the growth of bacteria and fungi in paint. In another related report, Lateef *et al.* (2016c) described AgNPs biosynthesized with hydrolyzed extract of nest of paper wasp. The crystalline polydispersed AgNPs had SPR at 428 nm, were anisotropic with the presence of sphere, triangle, hexagon, rod, and rhombus producing inhibition of MDR strains of *K. granulomatis* and *P. aeruginosa* with zones of inhibition ranging from 12-35 mm. The AgNPs totally suppressed *A. flavus* and *A. niger*, while 75.61 % growth inhibition was obtained against *A. fumigatus* at 100 µg/mL.

Elemike *et al*. (2016a) reported the antibacterial activities of 2-imino-(3,4-dimethoxybenzyl) ethane sulphonic acid borne on AgNPs through the activities of sugarcane. Sugar cane sap biofabricated AgNPs of 25-30 nm, which proved to be potential antibacterial agents against *S. aureus, E. coli,* and *S. aubeus*. Deshi *et al*. (2016) used different root extracts of *Waltheria americana* to synthesize AgNPs. The FTIR indicated anthraquinones, alkaloids, glycosides, tannin, terpenoids, saponins, phenols, and flavonoids as being accountable for the reduction of Ag^+ to AgNPs. Different degrees of growth inhibitions were obtained against *Proteus* species, *S. aureus*, *Klebsiella* species, and *Streptococcus* species. Lateef *et al.* (2016f) have described the process to produce AgNPs by employing cocoa pod husk extract (CPHE) that yielded well dispersed and largely spherical nanoparticles having sizes ranging of 4-32 nm. The CPHE-AgNPs exerted excellent antibacterial activities. In synergistic studies involving antibiotics such as ampicillin and cefuroxime, CPHE-AgNPs contributed to 42.9-100 % augmentation in the antibacterial efficacies of the antibiotics. Also, the inclusion of CPHE-AgNPs into white emulsion prevented the growth of several bacteria and fungi.

Oluwaniyi *et al*. (2016) studied the potential of leaf extract of *Thevetia peruviana* to produce AgNPs. The AgNPs had SPR of 460 nm, appeared spherical-shaped and averagely sized 18.1 nm. It displayed antimicrobial activities against fungal pathogens and bacteria by inhibition of 10-20 mm. Labulo *et al*. (2016a) investigated the biosynthesis and antimicrobial activity of AgNPs using the aqueous extract of *Garcinia kola*. Following the colour change indicating the synthesis of AgNPs, UV-visible spectrum displayed the characteristic SPR at 427 nm. The AgNPs having particle size of 10.4 nm inhibited the growth of *E. coli*, *Bacillus subtilis*, *S. aureus*, *K. pneumoniae*, *A. niger*, *R. stolonifer* and *C. albicans*. Also, Ojo *et al*. (2018) used *Syzygium cumini* leaf extract to produce AgNPs. The particles formed have antibacterial activities towards *E. coli, Salmonella typhimurium,* and *S. aureus*. Lateef *et al.* (2016g) examined the biosynthesis of AgNPs via activities of extracts of leaf (LF) and seed (SE) of *Synsepalum dulcificum* (miracle fruit plant). The polydispersed LF and SE-AgNPs had SPR at 440 and 438.5 nm respectively. The crystalline particles were spherical and had a dimension of 4-26 nm, which inhibited *P. aeruginosa* and *K. granulomatis*. Also, the AgNPs displayed tremendous potencies against fungi by inducing 100 % growth suppression against *A. flavus* and *A. niger*. However, 75.60 and 73.17 % growth inhibition was obtained against *A. fumigatus* by LF-AgNPs and SE-AgNPs respectively.

Ogunsile *et al*. (2016) employed the leaf extracts of *Synedrella* *nodiflora* and *Parquetina nigrescens* to synthesize AgNPs. The AgNPs were tested for antimicrobial potentials against ten pathogenic microorganisms, namely, *P. aeruginosa, E. coli, K. pneumoniae, S. aureus*, *B. subtilis, C. albicans, A. niger, Penicillium notatum, R. stolonifer,* and *S. typhi.* The results showed that both AgNPs have significant activities against the bacteria, but with lesser activities on a few of the tested fungi. Elemike *et al*. (2017b) used extract of leaf of *Lavandula* × *intermedia* to produce AgNPs of averagely 12.6 nm that inhibited *Klebsiella oxytoca*, *E. coli*, and *C. albicans* by 10-23 mm. Moreover, the pod extract of *Cola nitida* yielded the synthesis of AgNPs that was spherical and polydispersed in nature (Lateef *et al.* 2016b). The crystalline particles were 12 to 80 nm in size. The AgNPs displayed good antibacterial activities by efficiently inhibiting *P. aeruginosa, E. coli*, and *K. granulomatis* by 12-30 mm. When included in white emulsion paint, the AgNPs exhibited a total eradication of bacteria and fungi.

In addition, Azeez *et al.* (2017) investigated cocoa bean extract (CBE) to synthesize AgNPs. The CBE-AgNPs of 8.96-54.22 nm in size were spherical and moderately polydispersed. The CBE-AgNPs showed noteworthy activities against MDR strains of *S. aureus, E. coli*, and *K. pneumoniae* inhibiting them by 10-14 mm. It also promoted the actions of some antibiotics by 42.9-100 % through synergy and suppressed bacterial and fungal growth in paint. In another similar report, Elemike *et al*. (2017c) synthesized AgNPs by employing *Talinum triangulare* (water leaf). The spherical-shaped particles having a mean diameter of 13.86 nm displayed stronger antimicrobial actions in comparison with the plant extract and $AgNO_3$ when evaluated against *S. typhi*, *E. coli*, *B. subtilis*, *S. aureus* and *C. albicans*. Also, Elemike *et al*. (2017d) explored *Costus afer* in biosynthesis of CA-AgNPs using the leaf extract. CA-AgNPs were monodispersed and spherical with an average dimension of 20 nm and acted against Gram positive and negative bacteria.

Adebayo-Tayo and Popoola (2017) used exopolysaccharides (EPS) produced by two lactic acid bacteria (LAB) to synthesize AgNPs. EPS produced by *Lactobacillus casei* (LPW2E) and *Lactobacillus fermentum* (LPF6) in submerged fermentation facilitated biofabrication of AgNPs of 0.2-10 nm that inhibited *S. pyogenes*, *S. aureus*, *E. coli, K. pneumoniae,* and *Bacillus* species with zones of inhibition of 12-26 mm. Elemike *et al*. (2017e) demonstrated the antimicrobial potentials of biosynthesized AgNPs with leaf extract of *Eupatorium odoratum,* producing spherical-shaped particles of ~23.6 nm that inhibited growth of clinical isolates of *S. typhi*, *E. coli, S. aureus, Bacillus subtilis*, and *C. albicans,* with superior performance compared with the plant extract. Also, Elemike *et al*. (2017f) under different conditions of temperature and time synthesized AgNPs under the influence of leaf extract of *Lippia citriodora* having diameters of 23.8 and 25 nm at 90 and 50 ^{o}C, respectively. The AgNPs had improved actions towards *E. coli*, *S. typhi, S. aureus, B. subtilis,* and *C. albicans* in comparison with the extract only. Oladipo *et al.* (2017b) evaluated the potentials of bacterial extracts of some species of *Enterococcus* to synthesize spherical-shaped AgNPs, whose sizes ranged from 4-55 nm with activities against bacteria and fungi. Similarly, Adelere *et al.* (2017) biosynthesized AgNPs with seed extract of *Buchholzia coriacea* that possessed antimicrobial activities against *S. typhi, P. aeruginosa, E. coli, S. aureus, A. niger, A. fumigatus* and *A. flavus.* Elegbede *et al*. (2018a) exploited fungal xylanases to fabricate AgNPs of 15.21-77.49 nm in size that proved active on *P. aeruginosa, E. coli, S. aureus, K. granulomatis, A. niger, A. fumigatus* and *A. flavus.* Similarly, Lateef *et al.* (2018b) established the ability of leaf extract of *Petiveria alliacea* to synthesize AgNPs of 16.70-33.74 nm in size. The spherical-shaped particles inhibited the growth of *E. coli, S. aureus, K. pneumoniae, A. niger, A. fumigatus* and *A. flavus.* Aina *et al.* (2019) also demonstrated biofabrication of AgNPs using the stem extract of *Chasmanthera dependens.* The cubic-shaped biosynthesized AgNPs with a size range of 24.53-92.38 nm inhibited the growth of some bacteria.

Similarly, Jackson *et al*. (2018a) synthesized AgNPs employing the extracts of *T. occidentalis, V. amygdalina* and *Lasianthera africana.* The reddish-brown AgNPs that absorbed maximally between 371 and 451 nm displayed potent antibacterial actions. Further, Jackson *et al.* (2018b) utilized fruit juices of some *Citrus* sp to synthesize AgNPs. The AgNPs displayed activities against four tested bacteria. The extract of leaf of *Carica papaya* was also used in similar way (Jackson *et al.,* 2018c) to produce AgNPs with SPR obtained at 435 nm. The AgNPs was effective against some bacteria. Dada *et al.* (2018) investigated the operation parameter to synthesize AgNPs using the leaf extract of *Tithonia diversifolia.* The spherical-shaped AgNPs that had a size range of 10-26 nm which absorbed at 430 nm, was active against multidrug-resistant *E. coli, S. typhi*, *Salmonella enterica,* and *B. subtilis*. Elemike *et al.* (2018a) used palm sap of *Raphia hookeri* to synthesize AgNPs that absorbed at 420 nm with remarkable antibacterial activities. Leaf extract of *Artemisia afra* also yielded AgNPs with SPR of 423-438 nm that exhibited antimicrobial properties Elemike *et al.,* (2018b). The seed oil of *Jatropha curcas* was used by Musa *et al.* (2019) to fabricate AgNPs, with activities against *E. coli, S. typhi, S. aureus, A. fumigatus, A. flavus,* and *Mucor* species. *Tagetes patula* was also employed by Elemike *et al.* (2018c) to synthesize AgNPs of 14.8-42.8 nm in size using the leaf and the flower extract.

Furthermore, Osibe *et al.* (2018) synthesized stable AgNPs that absorbed at 425 nm using the extract of *Catharanthus roseus.* The spherical-shaped AgNPs of 2-15 nm in dimension displayed potency against *E. coli.* The stem extract of *Blighia sapida* has also been used to produce AgNPs that absorbed maximally at 350 nm, and found to be active against *S. aureus* and *E. coli* (Ojo *et al.,* 2018). Cell-free lysate of *Bacillus subtilis* was explored for the production of AgNPs by Maduabuchi *et al.* (2017) to obtain particles of 58.24-72.20 nm in size with tremendous activities against *C. albicans* and *P. aeruginosa.* Ashishie *et al.* (2018) have as well demonstrated phytosynthesis of AgNPs using *Kigelia africana* with approximate size of 10 nm that inhibited *P. aeruginosa, K. pneumoniae,* and *C. albicans.* Okeniyi *et al.* (2018) employed *Tectona grandis* leaf extract to produce AgNPs that acted on *E. coli, Serratia* sp., *P. aeruginosa, Bacillus* sp., and *Micrococcus varians.* Larayetan *et al.* (2019a) used the extract of aerial part of *Callistemon citrinus* to synthesize AgNPs with good antibacterial activities against *E. coli* 0157:H7, *Salmonella typhi*, *Vibrio alginolyticus*, *S. aureus*, *Listeria ivanovii*, *Mycobacterium smegmatis* and *Staphylococcus enteritis*. *Albizia chevalier* was reported by Khan *et al.* (2018) to synthesize AgNPs of approximately 30 nm in size that achieved 95 and 99 % killing of *S. aureus* and *E. coli* within 24 h. Bankole (2018) also used *Laportea aestuans* to synthesize AgNPs with SPR of 435 nm that was active on *B. subtilis, P. aeruginosa, S. typhi,* and *S. aureus. Hura crepitans* seed extract has been used to synthesize AgNPs with SPR obtained at 325 nm. The particles of sizes 2-5 nm were effective against *E. coli, S. aureus, E. aerogenes,* and *B. subtilis* (Jonathan *et al.,* 2018). Akinsiku *et al.* (2018) have utilized the leaf extract of *Canna indica* to synthesize AgNPs with SPR obtained at 421 nm. The AgNPs were effective on *S. pyogenes, E. coli,* and *C. albicans.*

5.1.1.2 Analgesic and anti-inflammatory activities

Chiguvare *et al.* (2018) utilized Buchu plant to synthesize AgNPs of mean size of 19.95 nm. The phytochemicals found in the ethanolic extract that included proteins, glycosides, flavonoids, alkaloids, tannins, and saponins were reported to facilitate reduction and capping of the particles. In mice, the AgNPs significantly reduced pain induced with 2.5% formalin in comparison with aspirin, and indicated for the management of pain. Avoseh *et al*. (2017) experimented hydrosol extract of *Acacia mearnsii* for the biosynthesis of AgNPs and evaluated the anti-inflammatory property. The appearance of a milky colour from a deep brown colour indicated the bioformation of AgNPs with SPR of 480 nm. The bioreduction and stabilization of the particles were ascribed to the bioactives of the plant. Formalin was used to induce inflammation, and results obtained indicated that the biosynthesized AgNPs were very effective and efficient, achieving the inhibition of about 76%.

5.1.1.3 Antioxidant, catalytic and sensing activities

Silver nanoparticles produced via leaf extract of *Artemisia annua* and *Sida acuta* (Johnson *et al.*, 2014) displayed high-quality antioxidant activity, especially at lower concentrations when analyzed by 1,1-diphenyl-2-picrylhydrazzyl (DPPH) assay using ascorbic acid as control. The AgNPs biofabricated using the extract of *B. safensis* (Lateef *et al.,* 2015d) was reported to show excellent antioxidant activities which were superior to quercetin and *β*-carotene standards in DPPH radical scavenging study. The IC_{50} of 15.99 µg/mL was obtained for AgNPs, and in the ferric ion reducing power assay, the AgNPs displayed antioxidant activities of 1.84-2.42 at 20-100 µg/mL. Spherical AgNPs synthesized by Elemike *et al*. (2017c) using leaf extract of *Talinum triangulare* averaged 13.86 nm in size and scavenged DPPH better than the extract, and with comparable performance with ascorbic acid. *Costus afer* extract-mediated AgNPs reported by Elemike *et al*. (2017d) also scavenged DPPH at different concentrations. The nanoparticles scavenged DPPH better than the leaf extract, while it had comparable action with ascorbic acid.

Cola nitida pod extract-mediated AgNPs (Lateef *et al.,* 2016b) also scavenged DPPH with IC_{50} of 43.98 g/mL and a ferric ion reducing antioxidant power (FRAP) of 13.62-49.96 % at 20-100 µg/mL. The CPHE-AgNPs biogenically synthesized using the pod extract of cocoa (Lateef *et al.,* 2016f) as earlier reported showed antioxidant activities against DPPH with IC_{50} of 49.70 µg/mL, while FRAP values of 14.44-83.94 % were obtained. Labulo *et al.* (2016b) also biosynthesized AgNPs employing leaf extract of *Detarium mirocarpum* to yield crystalline spherical-shaped particles of 17.05 nm. The antioxidant activities (DPPH assay, nitric oxide and total antioxidant capacity) of the AgNPs were ranked from moderate to good. Azeez *et al.* (2017a) investigated the effects AgNPs mediated by *C. nitida* pod extract on antioxidant activity, flavonoids and phenolic constituents of *Amaranthus caudatus*. Treatments with AgNPs of 25 to 150 ppm enhanced scavenging of DPPH by 6.4-43.38 % in the plant, with exposure to 50 ppm producing the least IC_{50} of 0.67 mg/mL. The occurrence of phenolics was improved by 1.98-68.19 % in treatments with AgNPs, while 7.20-35.80 % improvements in flavonoids were obtained for treatments with gradient concentrations of AgNPs.

Furthermore, Lateef *et al.* (2017) evaluated the potentials of four biosynthesized AgNPs for the scavenging of H_2O_2. The synthesized AgNPs using the extracts of cobweb, pod, seed and seed shell of *C. nitida* achieved 77.0-99.8 % scavenging of H_2O_2. Similarly, *Petiveria alliacea* leaf extract-mediated AgNPs (Lateef *et al.,* 2018b) were shown to scavenge H_2O_2 and DPPH by 89.02 and 70.69 %, respectively. Elegbede *et al.* (2018a) also reported xylanase-mediated AgNPs to have scavenged DPPH and H_2O_2 by 37.48-79.42 and 20.50-96.50 % respectively. Elemike *et al.* (2018b) have shown *Artemisia afra*-mediated AgNPs to scavenged DPPH by 49.17-78.12 % at concentrations of 25-100 µg/mL, which were higher than activities of 40.11-59.79 % displayed by the leaf extract of the plant. In several studies, it has been shown that biosynthesized AgNPs can modulate treated plants to improve their antioxidant activities. *Corchorus olitorius* grown with different levels of AgNPs increased the DPPH scavenging and ferric reducing abilities of the leaf extract by 1.8 and 4.94 fold respectively (Azeez *et al.,* 2019a). Azeez *et al.* (2019b) also showed that cocoa-bean mediated AgNPs can be used for osmotic dehydration of tomato slices with improved microbial quality and antioxidant properties. Tomato slices dehydrated with 75 ppm of AgNPs at 60 °C had DPPH scavenging activity of 88.31 % in comparison with 71.17, 42.28, and 67.31 % obtained for 75 ppm sucrose, 75 ppm NaCl and control (vacuum oven-dried) respectively. In the most recent study, Azeez *et al.* (2019c) showed that AgNPs produced using *Cola nitida* pod extract modulated antioxidant activities of *Moringa oleifera* that were exposed to lead and cadmium. The AgNPs improved DPPH and H_2O_2 scavenging activities of leaf extract of *M. oleifera* by 13.66 and 13.59 % respectively over the control sample. Furthermore, AgNPs ameliorated the deleterious activities of Pb and Cd in *M. oleifera*, with increased DPPH, FRAP and H_2O_2 scavenging activities compared to heavy metal-impacted *M. oleifera*.

Obot *et al.* (2013) reported honey-mediated synthesis of AgNPs, which was yellowish-brown in colour, displayed characteristic absorption at 450 nm, and it inhibited the mild steel corrosion. Johnson *et al.* (2014) examined the anticorrosion potentials of the AgNPs synthesized using leaf extract of *A. annua* and *S. acuta*. Through potentiodynamic polarization curves, it was shown that the AgNPs inhibited mild steel corrosion in 0.5M HCl.

Silver nanoparticles biosynthesized using the nest extract of paper wasp (Lateef *et al.,* 2016c) as earlier stated exercised about 93.1 % degradation effect on the malachite green. Elemike *et al*. (2016b) reported a simple synthesis of AgNPs using *Verbascum thapsus* flower extract with SPR of 412 nm. The spherical particles AgNPs were of 8.4-48.7 nm in size, and degraded nitrobenzene in the range of 79.5-87.5 %. Also, *Lippia citriodora*-mediated AgNPs using the aqueous leaf extract as earlier reported also degraded methylene blue under UV light irradiation (Elemike *et al.,* 2017f).

Olajire *et al*. (2017c) demonstrated desulphurization of model oil by AgNPs through the adsorption of dibenzothiophene (DBT). AgNPs synthesized using extracts of cobweb and pod of *C. nitida* were used to functionalize activated carbon of brewer's spent. Both AgNPs effected removal of DBT than the native activated carbon, with the cobweb extract-mediated AgNPs being the best with adsorption ability of 29.8 mg DBT/g adsorbent at 25 °C. Thus, the Ag nanoparticles-modified activated carbon can be of use in petrochemical industries due to its eco-friendly nature, simplicity, and high performance. Similarly, Olajire *et al.* (2017d) reported functionalization of composted agro-waste activated carbons with AgNPs to adsorb DBT with the highest performance of 26.9 mg DBT/g adsorbent at 298 K.

Furthermore, AgNPs biosynthesized using the leaf extract of *D. mirocarpum* by Labulo *et al*. (2016b) as earlier reported was also investigated for the ability to detect Fe^{3+} and Hg^{2+}. The results showed that the SPR of AgNPs was quenched at 430 nm, and can adequately sensed Hg^{2+} at 20-70 µg/mL, and Fe^{3+} at 10-40 µg/mL. The AgNPs synthesized using leaf extract of *T. triangulare* reported by Elemike *et al*. (2017c) have been used to modify multiwalled carbon nanotubes (MWCNT), and compare its performance with those of other electrodes. Results from cyclic voltammetry experiments revealed that AgNPs-functionalized MWCNT had the best conductivity, which can be deployed for electrocatalysis. Also, CA-AgNPs phytosynthesized by the aqueous extract of *C. afer* described previously was studied for electrochemical properties (Elemike *et al*., 2017d). The CA-AgNPs/ MWCNT-modified electrode transfers charge well; a property that can be explored as a sensor in assaying biological and environmental samples.

5.1.1.4 Larvicidal, antiplasmodial and antitrypanosomal activities

Bacillus safensis extract-mediated AgNPs (Lateef *et al.,* 2017d) as earlier described displayed larvicidal activities when tested against *Anopheles* mosquito larvae resulting in 100 % mortality within 12 h. The LC_{50} of 42.19 µg/mL was obtained. Adesuji *et al*. (2016) investigated the application of spherical *Cassia hirsute* mediated AgNPs against the larval stage of lymphatic filariasis vector (*Culex quinquefasciatus*), with larvicidal activities of LC_{50} of 4.43 ppm and LC_{90} of 8.37 ppm. The CPHE-AgNPs biogenically synthesized using the pod extract of cocoa (Lateef *et al.,* 2016f) also achieved 70-100 % activities against larvae of *Anopheles* mosquito in 2 h, with LC_{50} of 43.52 µg/mL

Silver nanoparticles biofabricated by Elemike *et al*. (2017e) using aqueous leaf extract of *Eupatorium odoratum* were spherical-shaped particles and 23.6 nm in diameter. In the 3rd and 4th instar larvae of *Culex quinquefasciatus,* the AgNPs were more lethal within 24 h of exposure with LC_{50} of 95.9 and 166.4 ppm respectively, while the plant extract had LC_{50} of 396.8 and 448.3 ppm against 3rd and 4th instar larvae, respectively. CBE-AgNPs previously reported to have been synthesized by Azeez *et al.* (2017) displayed potency (LC_{50}: 44.37 µg/mL) against larvae of *Anopheles gambiae*. Also, *Lippia citriodora* mediated AgNPs (Elemike *et al.,* 2017f) were potent against 4th instar of *C. quinquefasciatus.* Larayetan *et al.* (2019a) reported antiplasmodial and antitrypanosomal activities of *Callistemon citrinus* mediated AgNPs. Flower, leaf and seed extract-mediated AgNPs were potent against *Plasmodium falciparum* with IC_{50} of 2.99, 3.14 and 5.34 µg/mL, respectively. However, only the leaf extract-mediated AgNPs reduced *Trypanosoma brucei* population by 20 % at concentration of 50 µg/mL.

5.1.1.5 Anticoagulant and thrombolytic activities

Silver nanoparticles biofabricated through *B. safensis* extract (Lateef *et al.,* 2016e) was reported to have inhibited clotting of human blood, while it also displayed thrombolysis by dissolving pre-formed blood clot. Similarly, *S. dulcificum* mediated AgNPs (Lateef *et al.,* 2016g) as mentioned previously have displayed incredible blood anticoagulant activities, where clotting of blood samples was well prevented. The visualization of discrete red blood cells (RBC) as shown by microscopic examinations attested to the activities, and the micrographs were similar with those of conventional EDTA blood anticoagulant. Additionally, both AgNPs lyzed blood clots quickly with RBC seen under the microscope. AgNPs biosynthesized with nest extract (Lateef *et al.,* 2016c) also inhibited coagulation of blood, and entirely dissolved preformed blood clots (thrombus) within 5 min of reaction indicating its potent anticoagulation and thrombolytic properties. CBE-AgNPs previously reported to have been synthesized by Azeez *et al.* (2017) have also prevented coagulation of human blood.

Furthermore, Lateef *et al*. (2017) described the synthesis of crystalline CB-, KP-, KS-, and KSS-AgNPs which were 8-50, 12-80, 3-50, and 5-40 nm in size, respectively. All the synthesized nanoparticles showed exceptional anticoagulant activities with microscopic examination showing that the biconcave structure of RBC was fundamentally preserved. Also, all the AgNPs were able to lyse the formed blood clots and the percentage thrombolysis recorded were; 55.76, 60.46, 72.73 and 89.83 % for CB-AgNPs, KP-AgNPs, KS-AgNPs, and KSS-AgNPs, respectively. Similar studies in our laboratories have affirmed the anticoagulant and thrombolytic actions of green synthesized AgNPs (Elegbede *et al.,* 2018a; Lateef *et al.,* 2018a; Aina *et al.,* 2019) and we have also documented a review work on the nanomedical importance of MeNPs as anticoagulant, thrombolytic and theranostic agents, which can be useful for improved treatment of blood coagulation diseases (Lateef *et al.,* 2018a).

5.1.1.6 Anticancer activities

Bello *et al.* (2017) produced AgNPs with the fruit extract of *Hyphaene thebaica* that led to the formation of particles of ~ 20 nm with SPR at 430 nm. The particles displayed potency against cancer cells producing IC_{50} of 2.6, 4.8 and 6.8 mg/mL against prostate, breast and liver cancer cell lines respectively.

5.1.1.7 Agricultural applications

Eze *et al*. (2016a) biosynthesized AgNPs (termed Ag Neem nano) using leaf extract of *Azadirachta indica*. The Ag Neem nano reportedly have a mean particle size of 20 µm. *In vitro* and *in vivo* investigations showed bioactivity of Ag Neem nano solution against microorganisms causing yam rot. In the *in vitro* study, *Fusarium moniliforme* and *Lasiodiplodia theobromae* were exposed to 0.05 ml Ag Neem nano solution in varying concentrations, with MIC of 0.8 and 0.5 mg/mL produced against *F. moniliforme* and *L. theobromae*. Moreover, the sterile yam slices dipped in the Ag Neem nano solution and later exposed to cultured microorganisms were not infected by the rot-causing microorganisms. In another similar report, Eze *et al.* (2016b) investigated the potentials of AgNPs biosynthesized using the leaf extract of neem to control postharvest loss. The responses of yam to the application of AgNPs for the reduction of postharvest losses during storage were examined using *Dioscorea rotundata*, *D. alata* and *D. cayenensis*. The treated yam barn witnessed the reduction in temperature to provide cool surroundings for the yams. With the application of silver neem at 100 and 200 mg/mL, *D. rotundata* and *D. alata* had their dormancy period significantly extended, while that of *D. cayenensis* was also significantly increased at 200 mg/mL. Moreover, lengths of sprouts, loss in weight, and the incidence of rot witnessed significant reduction in *D. cayenensis* and *D. alata.* Although, silver neem did not contain toxic chemicals, it would be necessary to evaluate the toxicity of silver neem-preserved yam for safety of its consumption.

Studies conducted by Azeez *et al.* (2017a; 2019a, c) as earlier reported have shown that biosynthesized AgNPs can increase vegetative growth in *Amaranthus caudatus, Corchorus olitorius* and *Moringa oleifera* justifying their use in improving plant growth alongside induction of beneficial phytochemicals. There were improved indices of growth and physiology of *C. olitorius* treated with AgNPs (Azeez *et al.,* 2019a), and also suppression of fungal pathogens and nematode (*Meloidogyne* sp.) in the shoot of the plant. Similarly, in *Moringa oleifera,* treatment with AgNPs enhanced the survival and growth of the plant exposed to toxic levels of Pb and Cd, with the action of AgNPs facilitating the immobilization of the toxic metals in the soil, without appreciable uptake by the plant (Azeez *et al.,* 2019c). This represents an efficient means of remediation of polluted soil using nanoparticles, such that the soil could be available for farming activities.

5.1.2 Green synthesis of zinc nanoparticles (ZnONPs) and the applications

Mfon *et al.* (2017) synthesized ZnONPs using the leaf extracts of *Ocimum gratissimum* and *Vernonia amygdalina* of 11-99 nm and were deployed as nano-fertilizers in growing pale and black-seeded *Amaranthus cruentus,* with improved germination of the seedlings. *Ipomea asarifolia* leaf extract was employed to synthesize ZnONPs with good performance at removing bromophenol blue and eriochrome black T through adsorption (Ibrahim and Abdullahi, 2017). The use of plantain peel extract for the synthesis of ZnONPs catalyst has been demonstrated by Onubun *et al.* (2017) with particles size of 50.67 nm. Okeniyi *et al.* (2017) reported *Dialium guineense* mediated zinc nanoparticles that inhibited microbe-induced corrosion of metals. The particles inhibited microbial growth that compared favourably with the performance of antibiotics and even performed better in some cases. Ajayi *et al.* (2018) investigated the synthesis of ZnONPs using fruit juice of *Citrus sinensis,* and applied it as nano-additive for the electroplating of mild steel. It was concluded that the nano-additive enhanced the smoothness of the surface of mild steel, with electrodeposition increasing with time.

Ogunyemi *et al.* (2019) used different plant extracts that included *Olea europaea, Lycopersicon esculentum* and *Matricaria chamomilla* to synthesize ZnONPs. The biosynthesized nanoparticles inhibited the growth of *Xanthomonas oryzae,* which may be deployed to control bacterial blight disease in rice. Ezealisiji *et al.* (2019) also synthesized ZnONPs using the leaf extract of *Solanum torvum.* The stable and spherical ZnONPs with the size range of 34-40 nm was reported to adversely affect renal and hepatic function in rats when applied topically as ZnONPs-hydrogel composite at 0.5 and 1.0 %w/w over a period of 28 days. Alayande *et al.* (2019) biosynthesized ZnONPs using the leaf extract of *Amaranthus spinosus,* with the formation of particles that inhibited the growth of *Shigella dysenteriae, S. typhi* and *P. aeruginosa.*

5.1.3 Green synthesis of gold and bimetallic silver-gold nanoparticles

5.1.3.1 Antimicrobial activities

Abalaka *et al*. (2014) biosynthesized AuNPs via reduction of gold salt using leaf extracts of *Gomphrena celosioides* and *Prunus amygdalus*. The synthesized AuNPs displayed SPR at 500 nm and was active on *S. typhi, S. aureus,* and *P. aeruginosa* with zones of inhibition of 12.44-17.56 mm produced. Ojo *et al.* (2016) also reported bioformation of AuNPs and Ag-AuNPs utilizing *B. safensis*. The AuNPs and Ag-AuNPs synthesized exhibited a characteristic purple colour and absorbed maximally at 561 and 545 nm respectively. The AuNPs depicted uniform spherical particles, while the Ag-AuNPs were also homogeneously spherical with some irregular aggregation to form a rod-like structure. Both nanoparticles were polydispersed in circulation, with the sizes of 10-45 nm for AuNPs and 13-80 nm for Ag-AuNPs. The nanoparticles acted against *A. niger* and *A. fumigatus* with inhibitions of 66.67-90.78 %.

Cantharanthus roseus leaf extract was used by Shittu *et al.* (2017a) to synthesize AuNPs with SPR of 545.5 nm, and average dimension of 28.5 nm. The biofabricated AuNPs was potent against *S. pyogenes* and *S. aureus.* Similarly, Shittu *et al.* (2017b) biosynthesized AuNPs using the leaf extract of *Piper guineense* that was used as a carrier of lincomycin. The nanodrug formulation was active against *S. pyogenes* and *S. aureus* with the AuNPs facilitating the release of the conjugated antibiotic. Larayetan *et al.* (2019b) employed seed extract of *C. citrinus* to synthesize AuNPs of ~37 nm in size that inhibited the growth of bacteria. Elegbede *et al.* (2018b) reported fungal xylanases-mediated AuNPs with the bioformation of spherical and flower-shaped particles. The AuNPs of 4.88-123.99 nm in size produced inhibition of 26.8-44.3 % against *P. aeruginosa, E. coli, K. granulomatis* and *S. aureus*, but profound antifungal activities of 74-87 % against *A. niger, A flavus* and *A. fumigatus*. Adebayo-Tayo *et al.* (2019) utilized the exopolysaccharide and cell-free extract of *Wesiella confuse* to synthesize AuNPs that inhibited *E. coli.*

Lateef *et al.* (2016h) biosynthesized Ag-AuNPs with the aid of different parts of *C. nitida* that led to the development of dark-brown colour from light orange of the precursor. The TEM analysis showed near spherical morphology for the particles synthesized by leaf, seed and seed shell with a dimension of 17-90 nm, while anisotropic shapes of rod, hexagon sphere, and triangle of 12-91 nm in size were reported for the pod extract-mediated particles. The four samples of Ag-AuNPs examined for potential antifungal activities yielded growth inhibitions of 76.83-100 % for *A. fumigatus* and 69.51-75.61 % for *A. niger*. Similarly, Elegbede *et al.* (2019) evaluated fungal xylanases in facilitating the production of Ag-AuNPs which absorbed at 520-534 nm. The anisotropic particles with dimension of 6.98-52.51 nm showed potent antibacterial (23.40-90.70 %) and antifungal activities (70.10-89.05 %).

5.1.3.2 Antioxidant and catalytic activities

Oladipo *et al*. (2017a) described the green synthesis of AuNPs through cell-free extracts of *Enterococcus* species leading to bioformation of blue-black colloids with SPR shown at 549-552 nm. The fairly spherical particles were crystalline and sized 8-50 nm. The AuNPs showed DPPH radical scavenging activities of 33.24-51.47 %. Similarly, Elegbede *et al.* (2018b) reported DPPH scavenging activities of 42.91-53.79 % at concentrations of 10-100 μg/mL for xylanases-mediated AuNPs, while the particles scavenged H_2O_2 by 74-96 %. Sodeinde *et al.* (2016b) employed the extract of *Chrysophyllum albidum* with the assistance of microwave to synthesize Ag and Ag-Au nanoparticles for the electrooxidation of methanol as novel nanocatalysts.

The AuNPs and bimetallic Ag-AuNPs biosynthesized with the aid of *B. safensis* (Ojo *et al.,* 2016) have been reported to display brilliant dye degradation potentials against malachite green (> 90 %) in 48 h. Bimetallic Ag-AuNPs biosynthesized by Lateef *et al.* (2016h) using different parts of *C. nitida* degraded methylene blue (MB) and malachite green (MG) by about 60 and 90 % respectively after 24 h of reaction. AuNPs biofabricated with the aid of *Enterococcus* species (Oladipo *et al.,* 2017a) also degraded MB and MG by 24.3-57.6 % and 88.85-97.36 %, respectively in 24 h. Ag-AuNPs synthesized by Elegbede *et al.* (2019) were also reported to scavenge DPPH by 48.51-53.79 % and hydrogen peroxide by 80.5-95.50 %. In addition, malachite green was degraded by the particles by 91.39 %, while maximum degradation of 47.10 % was achieved with methylene blue.

5.1.3.3 Larvicidal and antitrypanosomal activities

The bimetallic Ag-AuNPs biosynthesized by Lateef *et al.* (2016h) using four different parts of *C. nitida* displayed larvicidal capacities against larva of *Anopheles gambiae* with 100 % mortality achieved at different concentrations of the Ag-AuNPs (60-100 μg/mL) within 3-72 h. AuNPs biofabricated with *Enterococcus* species (Oladipo *et al.,* 2017a) were effective against larva of *Anopheles gambiae* with LC_{50} of 21.28-42.33 μg/mL at 12 h of exposure. Larayetan *et al.* (2019b) have shown that biosynthesized AuNPs using seed extract of *C. citrinus* killed *Trypanosoma brucei* with the IC_{50} of 11.06 μg/mL. Shittu *et al.* (2018) biofabricated AuNPs using leaf extract of *Hyptis suaveolens,* which was functionalized with diminazene aceturate and formulated as nanodrug using polyhydroxylbutyrate. It was reported that the nanodrug reduced the population of *Trypanosoma brucei* and lowered the toxicity of diminazene aceturate in rat, thereby serving as effective means of drug delivery.

5.1.3.4 Anticoagulant and thrombolytic activities

The AuNPs and bimetallic Ag-AuNPs biosynthesized with extract of *B. safensis* were also revealed to possess anticoagulation and thrombolytic activities (Ojo *et al.,* 2016). Both nanoparticles inhibited coagulation of blood which was stable over a long period of time and nanoparticles also prompted the dissolution of the blood clot, and nature of the nanoparticles-anticoagulated blood and dissolved blood clot was observed by optical microscope which showed good comparison with the fresh blood sample. The bimetallic Ag-AuNPs biosynthesized by Lateef *et al.* (2016h) with four parts of *C. nitida* and those mediated through the activities of fungal xylanases (Elegbede *et al.,* 2019) as reported earlier prevented the coagulation of fresh human blood comparable to what was obtained with EDTA. Also, the samples of Ag-AuNPs dissolved preformed human blood clots quickly. Different AuNPs biofabricated using *Enterococcus* species (Oladipo *et al.,* 2017a) halted blood coagulation and also lyzed blood clot by 9.4-94.6 %, indicating potential nanomedical applications. Similarly, xylanases-mediated AuNPs (Elegbede *et al.,* 2018b) have been reported to display potent anticoagulant and thrombolytic activities using human blood.

5.1.3.5 Anticancer activities

Hampp *et al.* (2012) biosynthesized AuNPs using *Bacillus megaterium*. Investigations using atomic force microscope (AFM) revealed 6-times adhesion of AuNPs with breast cancer cells in comparison with normal breast cells. Also, the activity was thrice the value obtained for chemically-prepared AuNPs. Similarly, binding of the breast-specific antibody to breast cancer was facilitated by AuNPs, which had adhesion power that was five times that of noncojugate. Dozie-Nwachukwu *et al.* (2017a) biosynthesized AuNPs and gold/prodigiosin nanoparticles. Prodigiosin is a secondary metabolite produced by *Serratia marcescens* that has been known to have anticancer, cytotoxic, antiproliferative and antibacterial properties. The particles ranged from 20-120 nm for the cellular and cell-free extract mediated AuNPs, while 40-50 nm was the range for prodigiosin-gold nanoconjugate. Application of AuNPs and gold-prodigiosin nanoconjugate for localized cancer treatment was therefore advanced.

Similarly, Oni *et al.* (2016) studied adhesion of AuNPs with paclitaxel under the influence of antibody-based molecular recognition units (MRU). Through measurements under AFM, AuNPs enhanced the adhesion of cancer cells with the anticancer drug. As a result of the positive results obtained, design of robust AuNPs cluster and applications in hyperthermia and localized delivery of drugs were further discussed. Dozie-Nwachukwu *et al.* (2017b) have shown that AuNPs/prodgiosin conjugate produced using *N. latifolia* and *S. marcescens* increased the adhesion to triple cancer cells (MDA-MB-231) than normal breast cell by about five times. Therefore, the conjugated nanoparticles can be useful to treat cancer. Shittu and Stephen (2017) employed the extract of *Nelsonia canescens* to biofabricate AuNPs of ~50 nm size and with SPR obtained at 537.5 nm. The particles were active against MCF-7 cell line with IC_{50} of 0.455 mg/L. Earlier, Shittu and Stephen (2016) explored the possibility of developing eco-friendly metallic AuNPs using aqueous leaf extracts of *Calotropis procera*. The particles with SPR of 550 nm that averaged 45 nm in size decreased the viability of MCF-7cell with IC_{50} of 0.312 mg/L. Most recently, Botha *et al.* (2019) biosynthesized AuNPs and Ag-AuNPs with aid of leaf extract of *Solidago canadensis* and studied their effects against HuTu-80 and H4IIE-*luc* cells. It was reported that the bimetallic particles showed very high potency against the cells, while AuNPs was not toxic to the cells.

5.1.4 Green synthesis of iron, magnetic, nickel and carbon nanoparticles and their applications

Obayemi *et al.* (2015) biosynthesized magnetite nanoparticles (BMNPs) using *Magnetospirillum magneticum*. The nanoparticles displayed SPR at 450 nm, while the TEM micrographs obtained indicated particle shapes of prism, rectangle, sphere, and cube with a dimension of 10-60 nm. Functionalization of BMNPs with luteinizing hormone releasing hormone (LHRH) showed that BMNPs can be deployed to specifically target cancer cells for their treatment.

Akinsipo *et al.* (2016a) investigated the applicability of iron nanoparticles (FeNPs) greenly synthesized using the extract of mango leaves as a Fenton-like catalyst for photocatalytic degradation of dye effluents. Characterization of the material with SEM and FTIR showed the presence of iron oxide and iron oxohydroxide in the FeNPs. Congo red and malachite green were degraded with the FeNPs in a photodegradation experiment. The biosynthesized iron nanoparticles were also used as a Fenton-like catalyst which assisted degradation of the dye using H_2O_2. It was inferred that the degradation of dyes at various industries such as food and textiles can be achieved using the FeNPs. Ituen *et al.* (2019) advanced the production of FeNPs via peel extract of *Musa sapientum* and reported its anticorrosion activity. While the peel extract inhibited corrosion of mild steel by 72.1 %, the extract-mediated FeNPs achieved anticorrosion of 94.4 % in 1M HCl. The study concluded that the FeNPs could find application as an anticorrosive additive in the oilfield. Akinsipo *et al.* (2016b) described a facile synthesis of chitosan-magnetite nanoparticles (CS-MNPs). MNPs and CS-MNPS had diameters of 38 and 42 nm, respectively. Magnetic release and delivery process were examined in an *in-vitro* experiment by employing phosphate buffer medium of pH 7.4. The *in-vitro* release profile indicated a slower and controlled release of magnetite nanoparticles from chitosan shell for a 12-h period. Thus, CS-MNPs displayed promising potential that may overcome side effects such as site toxicity and specificity.

Konne and Okpara (2014) investigated the bioremediation potentials of magnetic nanoparticles stabilized with starch (SSMNPs) which was prepared by reacting $FeCl_3.6H_2O$ and $FeCl_2.4H_2O$ together under the influence of different concentrations of cassava waste water. XRD investigation showed the presence of magnetite nanoparticles in all the samples with the particle size of 11.48-17.73 nm. The SSMNPs that had the lowest concentration of displayed highest activity of 93 % at removing nickel in crude oil. Konne *et al.* (2015) further studied SSMNPs as adsorbents to remove lead, cobalt and nickel from aqueous media, whereby SSMNPs performed better than unmodified MNPs at removing cobalt and lead.

Kareem *et al.* (2017) advanced the use of MNPs to purify crude lipase produced by *Aspergillus flavus.* At temperature of 25°C and under shaking, MNPs bound other proteins, while unbound protein was removed by applying an external magnetic field with elution with 0.8 M NaCl in ammonium acetate buffer. The single step purification using $MnFeO_4$ magnetic nanoparticles led to attainment of purification, enzyme yield and specific activity of 20.53-fold, 59 % and 11.29 U/mg, respectively. Electrophoretic separation of the enzyme on SDS PAGE produced a single band when stained with Coomassie brilliant blue, which corresponded to the molecular weight of 35 kDa.

Mamuru and Jaji (2015) biosynthesized nickel nanoparticles using leaf extract of *Moringa oleifera*. The clustered dark reddish-brown nickel nanoparticles absorbed maximally at 297 nm. Voltammetric and impedimetric behaviour of the particles showed superimposed porous layer attributes of the particles with very high values for transfer of electrons. The results obtained can justify the application of the particles to fabricate biosensors and in catalytic reactions.

Adedokun *et al*. (2017) described a green and cost-effective synthesis of highly fluorescent carbon nanoparticles (CPs) using the fruit peel of *Citrus sinensis*. The biosynthesized CPs showed bright blue fluorescence when irradiated at 365 nm. The presence of several functional groups on the surface of CPs has the potential to influence its adsorption characteristics that can be explored for the treatment of wastewater. Also, the negative zeta value of the CPs can justify its potentials to selectively adsorb cationic dye from mixture of dyes. The biosynthesized CPs rapidly adsorbed methylene blue by about 84 % in a minute of reaction.

5.2 Renewable energy

Ahmed *et al*. (2013) described the use of dye extract of *Hibiscus sabdariffa* as a sensitizer for nanosized titania (TiO_2). The SEM micrographs revealed that the spherical particles formed had diameters of 25-40 nm. The synthesized dye-sensitized solar cell (DSSC) was studied with current density, open-circuit voltage (V_{oc}), fill factor (FF) and power-conversion efficiency (η) of 0.17mAcm^{-2}, 460 mV, 41 % and 0.033 %, respectively. The performance of DSSCs offers cheap, stable and renewable solar cells than can be commercialized on a large scale. Boyo *et al*. (2013) explored the applications of methanolic extracts of calyxes of *Azardirachta indica* and leaf of *H. sabdariffa* as sensitizers in DSSCs. The values obtained for solar energy conversion efficiency was 0.002 %, while fill factor, current density and V_{oc} were 0.739, 4.5mAcm^{-2} and 0.0124mV, respectively for *H. sabdariffa*. The conversion efficiency, fill factor, current density and V_{oc} of *A. indica* were 0.00017 %, 0.4, 2.5mAcm^{-2} and 0.0118mV, respectively. The presence of anthocyanins in *H. sabdariffa* which binds TiO_2 to minimize losses was adduced for better performance *H. sabdariffa*-DSSCs. However, the conversion efficiency is in doubt for energy application.

Moreover, Eli *et al*. (2016a) reported improved performance of a DSSC using AgNPs-modified fluorine tin oxide (FTO) electrode through successive ion layer adsorption and reaction (SILAR). The results obtained indicated that photocurrent and V_{oc} of DSSC were significantly improved by AgNPs. The modification led to approximately 22 % improvement in photocurrent over that of bare FTO without AgNPs. Similarly, Eli *et al*. (2016b) modified DSSC with AgNPs through the implementation of SILAR, which brought enhanced performance. AgNPs-modified DSSC yielded an efficiency (η) of 0.065 %, which is 63 % improvement in efficiency, 48.4 % augmentation in short circuit current density and 8.5 % improvement in open circuit voltage as influenced by absorption strength of AgNPs due to its SPR. Furthermore, Eli *et al.* (2016c) studied the impact of TiO_2 nanoparticles in DSSC through the dye of *H. sabdariffa*, with improved solar conversion efficiency (η) of 0.0067 %. Similarly, Onimisi *et al*. (2016) examined the effects of AgNPs on the performance of DSSCs via SILAR. Sizes of AgNPs affected the performance of the modified cells, with the best conversion efficiency (η) of 0.00910 % that translated to 36 % improvement.

5.3 Toxicological investigations of green synthesized nanoparticles

Yekeen *et al.* (2017a, b) have carried out studies on the evaluation of genotoxicity of green synthesized AgNPs using the *Allium cepa* assay (Bakare *et al.,* 2003; Lateef and Yekeen, 2006; Lateef *et al.,* 2007). In both cases, AgNPs (0.01-100 µg/mL) biosynthesized using extracts of *C. nitida* pod, seed, and seed shell (Yekeen *et al.,* 2017a), as well as cocoa pod and bean (Yekeen *et al.,* 2017b) were potentially cytotoxic and induced some chromosomal aberrations in *A. cepa*. It was concluded that the mito-depressive action of the AgNPs could be exploited in the development of cytotoxic drugs in the treatment of cancer. The studies concluded that indiscriminate usage of AgNPs might pose some health issues in exposed organisms.

5.4 Review articles/works

There have been several contributions by Nigerian scholars on topical issues in nanotechnology policy, research, and development which are reviewed as follows:

5.4.1 Awareness, development and policy issue on nanotechnology

Ulaeto *et al*. (2013) reported that in spite of the advances and cutting-edge development in various industries that nanotechnology has brought in technologically developed countries, little is known about its potentials and risks in the developing countries around the world especially among undergraduates in universities. The study examined the awareness, risk and benefit perceptions of nanotechnology among undergraduate students from some universities in Nigeria. A survey tool comprised of 30 structured questions that involved 110 respondents from both public and private universities within four geopolitical zones in Nigeria was undertaken. It was revealed that about 62.3 % of respondents had little to no understanding or basic knowledge of nanotechnology, while only 37.7 % had the basic knowledge, although a majority, about 77.4 % of respondents had some level of knowledge of the word 'nanotechnology', but their perceptions of its benefits and risks were poor. The survey affirmed that an effective understanding of perceptions of nanotechnology by the undergraduate students is critical for the realization of technological advances in a developing country like Nigeria. Thus, there is a critical need to tutor them about the promising and rapidly growing field of nanotechnology and its various applications.

Similarly, Kallamu (2013) reviewed the understanding of nanotechnology for national development. It was emphasized that the emergence of the discipline has given way to several potentials that can bring about novel changes in diverse fields of science and technology, thereby necessitating its popularization to create awareness of its importance and impacts on different professions. The report also identified the importance of nano fluids in solar thermal engineering because nanofluids are utilized to enhance the performance of systems in several thermal engineering processes.

Furthermore, Akpan (2014) assessed the quantity of work done so far in areas of nanotechnology in Africa with a view to identifying key areas where more work should be concentrated. It was found out that environment, health and energy are the three important areas that call for nanotechnology inputs in Africa. The extent of published articles and patents achieved were used as scientometric indicators for assessing nanotechnology development in Africa. The results of the scientometric analysis indicated that 23 Africa countries produced 1,775 publications over the period of 1995-2011. In-depth analysis revealed that nanotechnology-related research on the continent was concentrated largely in six countries (South Africa, Egypt, Tunisia, Algeria, Morocco and Nigeria) which accounted for about 97 % of the continent's publications in peer-reviewed Thomson Reuters impact factor Journals. The inventive profile was also examined and it was found out that in patents, Africa produced about 0.061% (41 patents) of the world's nanotechnology related inventions. Moreover, about 88 % of Africa's inventive activities were concerted in South Africa, while Egypt and Morocco shared about 12 %. Bankole *et al*. (2014) explained that nanotechnology has raised awareness and attention in recent times and has emerged as a leading alternative contemporary clean technology in this century. But despite the vast benefits of nanoscience and nanotechnology, Nigeria has not yet developed nanotechnology programme and scheme to enhance her development socio-economically including the transformation of her other important sectors. Nanotechnology controls the properties of matters and also has the capacity for the creation of new materials of definite properties, which are capable of being utilized for specialized functions. Thus, it has the hope of reshaping and redefining humanity and human conditions, while also reducing pressures on existing natural resources. Policy makers in Nigeria, non-governmental organizations and the general public were therefore called upon to make significant contributions to nanotechnology development in the country.

Also, Ezema *et al.* (2014) examined the evolution of nanotechnology in some countries that included USA, China, Japan, Germany, UK, and Russia by reviewing their road maps in nanotechnology. Factors such as funding, human resource development, public and private initiatives, industrial capabilities, and focus were considered with the view of drawing inferences that could be an example to Africa and other developing nations in their journey to benefit from advances in nanotechnology. The investigation which employed analysis of open access literature revealed that European countries, USA, and the Asian giants of China and Japan were the topmost players in nanotechnology. However, countries like Singapore, Brazil, India, Malaysia, Thailand, and South Africa were identified as those developing capacities in R & D on nanotechnology. African nations largely were reported to be at the least stage of "demonstration of interest" without budget allocated to nanotechnology. The article underscored the roles of cooperation, collaboration and partnership among critical stakeholders in African countries to pool resources together to advance nanotechnology development in Africa.

5.4.2 Nanotechnology in pharmaceutics, healthcare and medicine

Putheti *et al*. (2008) investigated the significance of nanotechnology in pharmaceutical development. The various types of nanoparticles for drug delivery systems, physicochemical formulations such as size, surface and particle morphologies, and structures that emphasizes the characterization of nanoparticles, and drug release techniques were discussed. It was highlighted that nanoparticle-based drug delivery systems are appropriate to treat persistent intracellular infections such as tuberculosis. Also, the use of nanostructured lipid carriers (NLC) and solid lipid nanoparticles (SLN) as the latest mean to deliver antifungal drugs in dermatology and future directions in applications, especially in oncology was discussed. It was concluded that nanotechnology has evolved to solve challenges in pharmaceutical formulation which include solubility enhancements, reduction of time for research and developments, and cost of production, faster time-to-market for newly developed drug and more efficient and discriminatory targeting of cells and pathogens that lower dosage of drugs.

Ochekpe *et al.* (2009a) discussed nanotechnology in the natural world, its history and methods of production, while its applications, benefits and risks were also outlined. Nanotechnology was observed to be a revolution in manufacturing processes as an outcome of knowledge integration that could have a positive impact on man. Also, the applications of nanotechnology in a drug delivery were discussed as it is seen as an approach designed to surmount constraints in drug delivery systems. Through the development and fabrication of nanostructures, numerous advantages which include shielding of drugs encapsulated within them against hydrolysis and attack by enzymes in the gastrointestinal tract; targeting, and specific delivery of drugs for sustained release over a certain period of time could be attained. It was concluded that nanotechnology is a multidisciplinary that must be funded by governments to bring about improvement in healthcare, renewable energy, potable water, sustainable agriculture and clean environment. In another related review, Ochekpe *et al.* (2009b) emphasized that Nanotechnology is a concept that is geared to surmount challenges of traditional drug delivery systems on the basis of the development and manufacturing of nanostructures. The diverse kinds of nanostructures (such as polymeric nanoparticles, liposomes, dendrimers, solid lipid nanocarriers, polymeric micelles, nanocapsules, ceramic nanoparticles, metallic nanoparticles etc) utilized in drug delivery, their techniques of fabrication and the challenges of nanodrug were highlighted. Some issues related to its impacts on drug effectiveness, stability, pharmacokinetics, toxicity and drug regulatory control were discussed. Also, some commercially available nano-based drug delivery systems were highlighted.

Additionally, Num and Useh (2013) in highlighting diseases as a major drawback in livestock production have argued in favour of developing of new analytical and curative systems to attain animal protein sufficiency for human nutrition. The trajectory of search for efficient diagnosis has traversed traditional methods to molecular and now nanotechnology. It was reported that nanotechnology is at present being used to treat African animal trypanosomiasis, where porous cationic nanoparticles are employed at improving targeting of trypanosomes. Also, pre-treatment of mice with protein cage nanoparticles (PCN) has been found to confer protection on mice against influenza viruses, mouse pneumovirus and mouse-adapted SARS-coronavirus. The significance of nanotechnology in other areas of veterinary diagnostics and therapeutics towards improvements were discussed.

Abiodun-Solanke *et al*. (2014) stressed the concept of nanotechnology as that with limitless possibilities and potentials; one of which is its entry to dentistry that has given rise to the latest sub-field of nanodentistry. The study assessed electronic databases such as MedLine, PubMed, and Cochrane using keywords like nanotechnology, dentistry and applications to identify articles that were published in English between 2008 and 2013. The exercise revealed eight articles, where authors have reported several advances of nanotechnology in dentistry that included diagnosis of oral cancer, use of nanoparticles as sterilizers against pathogens, incorporation of calcium nanoparticles in toothpastes to enhance remineralization of early enamel lesions, and replacement of the whole tooth through combination of nanotechnology, tissue and genetic engineering. It was concluded that nanotechnology is undoubtedly set to transform dental practice and projected that in no distant future, dental surgeons will find oral health care services less stressful, more tolerable for patients and the outcomes will appreciably become more favourable.

Onyenanu *et al*. (2014) in a study that evaluated recent advances of nanotechnology with high potential to detect and treat cancer in humans noted that current results have positioned nanotechnology to offer new hope in the prevention, detection and treatment of cancer. Cancer being a compound disease triggered by genetic instability and build-up of multiple molecular alterations in human beings has taken adequate medical research attentions in recent times. Nanoparticles formulation are said to be advantageous over conventional chemotherapy because they can incorporate several diagnostic and therapeutic agents and are associated with considerably less adverse effects due to selective accumulation to tumour tissue. Thus, nanoparticles can be engineered or designed to target specific tumour cells that express particular cell surface molecules. It was concluded that the selection of appropriate targets, component materials, and formulation strategies are critical to achieving successful outcomes in such endeavours.

Similarly, Lateef *et al.* (Lateef *et al.,* 2018a) presented the trends in the potential nanomedical applications of various MeNPs to manage blood coagulation issues. It was emphasized that one of the foremost health problems in recent years is cardiovascular disease, which is heralded by coagulation disorders with high global mortality. Nano-based drugs can solve problems of exorbitant cost, short-term action, allergic reactions, and other side effects that accompany the administration of conventional anticoagulant and thrombolytic drugs. The review underscored the relevance of MeNPs to manage blood coagulation disorders; particularly in anticoagulation, thrombolysis, imaging and theranostics.

Moreover, Elegbede and Lateef *et al*. (2019) highlighted the recent advances and trends in the biosynthesis of Ag, Au, and Ag-Au alloy nanoparticles for biomedical applications. The antimicrobial, antioxidant, larvicidal, anticoagulant and thrombolytic activities of these greenly synthesized metallic nanoparticles were examined including the discussion of properties of the nanoparticles. These biomedical applications are situated to combat the numerous of problems facing mankind; predominantly the antimicrobial resistance phenomena, control of vector-borne diseases, mitigation of the deleterious effects of free radical species among others. The review underscored the importance of these nanoparticles in the emerging disciplines of nano- and biomedicine.

5.4.3 Biosynthesis of nanomaterials

Agharkar *et al*. (2014) presented a summary of procedures for one pot reduction of graphene oxide (GO) and metal precursors to fabricate graphene decorated with nanoparticles using bacteria {(*Shewanella*, *Bacillus subtilis*, extremophilic bacteria, *Escherichia coli* and *Gluconacetobacter xylinus*), phytoextracts (*Gingko biloba*, *Camellia sinensis* (green tea), *Daucus carota* (wild carrot), *Amaranthus dubius*, *Citrus sinensis* (orange), *Cocos nucifera* (coconut)} and biochemicals such as L-cysteine, L-glutamine, vitamin C, glucose, fructose, and sucrose. The review showed various routes through which graphene can be produced via green synthesis.

Adelere and Lateef (2016a) presented a study aimed at compiling reports on the exploitation of agro-wastes, enzymes, microbial and plant-derived pigments for the green synthesis of metallic nanoparticles which was reported to be on the increase in recent times considering the vast field of applications. About twenty-three (23) agro-wastes, six (6) enzymes, and eight (8) plant-derived pigments were highlighted to have been effectively used to biofabricate MeNPs for several applications. Thus, nature holds vast bioresources that would continue to play prominent roles in green nanotechnology.

Lateef *et al*. (2016i) also highlighted the promising roles of metabolites of arthropods in the facile synthesis of MeNPs. The review recognized the significance of arthropods in biosynthesis of metallic nanoparticles, which navigates the exploit of arthropods such as bee, spiders, silk worm and their metabolites from honey bee, cobweb, silk fibroin, sericin and paper wasps, among others. The abundant bioactive molecules present in arthropods can function as inputs for the green synthesis of nanoparticles of specific properties suitable for potential applications in nanomedicine.

5.4.4 Nanotechnology and energy

Okeke and Iloanusi (2014) showed that the traditional energy system has failed in a lot of ways, and a more reliable energy system infrastructure will be required to contribute to a more energy secured society. Nanotechnology leads to the creation of more efficient products which are being employed at different layers of the energy system architecture for more efficient and optimal energy systems. Technological innovation at the nano-scale is seen as a major driver for the uptake of renewable for sustainable energy systems of the future. Thus, the roles of nanotechnology in improving energy system reliability were presented along the lines of the major aspects of the energy infrastructure, which are; production, distribution, storage and utilization.

6.0 Gaps in green nanotechnological research in Nigeria

The critical areas where Nigeria needs intensive research activities in nanotechnology are applications in agriculture, availability of clean water, medicine/healthcare, pollution control and renewable energy. Most of the researches conducted so far are at the lowest rung of investigations, which have not been translated to products to benefit the teeming population of Nigeria. An appraisal of the investigations also showed the dominance of synthesis of AgNPs; followed by AuNPs, while activities are at low ebb for other metallic nanoparticles (Table 1). Similarly, most investigations have been on antimicrobial studies, with scanty reports on other investigations. Obviously, there is the need to expand the biosynthetic route to other metal nanoparticles as well as increasing the scope of applications, toxicological and life cycle assessment analyses. These efforts would require multidisciplinary investigations by researchers of different specializations to develop nano-based products and conduct translational studies.

Furthermore, research conducted in the potential applications of green nanotechnology in the field of agriculture in Nigeria is still very little compared to the vast benefits that nanotechnology possesses in aiding improved crop yield, fertilizer and manure applications, toxicology studies, improved plant growth, reduction in time of maturation of crops, animal health, genetics, control of pest and diseases, storage, control of fruit ripening, and wastages among others. Another gap in research activities of Nigerian institutions in the green synthesis of nanoparticles is in the involvement of enzymes, microbes, metabolites of insects and wastes of higher animals in the synthesis of novel nanocatalysts. Very few reports exist in this aspect of green synthesis compared to the use of plants in the synthesis of nanoparticles. Synthesis of nanoparticles that are enzyme-based can have potential applications in industrial processes, while the nanoparticles from metabolites of insects can have various potential applications in nanomedicine, especially in drug delivery. There is also lack of data on applications of nanoparticles in bioprocess development to improve activities of microbes in the production of bioproducts such as biogas, biohydrogen, bioethanol, single-cell proteins, and organic acids among others. These highlighted areas may be of interests to researchers in microbiology, biochemistry and zoology to unlock the potentials of the aforementioned materials in nanobiotechnology.

Another major concern in green nanotechnology research among Nigerian Universities is the number of patents which is ridiculously low or almost nonexistent. Although Nigeria ranks among one of the six countries actively involved in nanotechnology research which contributed up to 97 % of Africa's publications in peer-reviewed journals, Akpan (2014) reported that about 88 % of Africa's inventive activities were concerted in South Africa, while Egypt and Morocco shared about 12 %, leaving Nigeria and other African countries at about 0 % of inventions in nanotechnology research. In actual fact, most of the research activities in nanotechnology in Nigeria have been in collaboration with different institutions in South Africa (Table 1).

7.0 Challenges

The education policy in Nigeria has gone through a lot of developments since the launching of National policy on education in 1977 (Amaghionyeodiwe and Osinubi, 2006), because education has been regarded as an instrument of change that can foster cohesion among citizens and promote self-realization with improved national productivity for the overall development of the nation. However, there have been recurring challenges bedevilling education sector in Nigeria that has forestalled the realization of the intention of national policy on education. Some of the challenges of research, particularly nanotechnology research in Nigeria are highlighted in this study.

7.1 Funding

Inadequate funding of education is a recurring problem in Nigeria. In attempt to solve the problem, the Education Tax Fund (ETF) (Now Tertiary Education Trust Fund, TETFund) came to existence through a decree in 1993 to fund projects in tertiary institutions, through education tax imposed on companies operating in the country (Jaja, 2014). However, this effort is not yielding the deserving results because as noted by Amaghionyeodiwe and Osinubi (2006) the national budget on education has been dwindling and often less than 10 % (typically between 9.9 and 7.6 %). Adeyemi (2011) indicated that the general funding of education in Nigeria has never reached 17 % in any particular year in spite of UNESCO minimum standard of 26 % of national budgets. In 2018, education sector accounted for only 7.14 % of the federal budget, which stood at N651.2bn to cater for allocations to universal basic education programme, 104 federal government colleges/unity schools, federal government-owned tertiary institutions (universities, polytechnics and colleges of education), and special intervention programme of TETFund.

The twin problems of inadequate funding and over-bloated students' population are major causes of deterioration of quality in the education sector of the country. With the overstretching of facilities, insufficient fund further compounds deterioration and collapse of infrastructure, shortages of recent books and contemporary journals in the libraries, lack of appropriate equipment and consumables in the laboratories, and inadequate grants for cutting-edge research (Moja, 2000). Nanotechnology is a cutting-edge discipline that requires expensive and the state-of-the-art analytical equipment and facilities for its studies. The fund allocated to higher education institutions has been insufficient, with the model not even reflecting inflation rates and the growing employment figures in recent years. There must be concerted efforts to mobilize fund for education sector in Nigeria, as well as reengineering of resource utilization and management in the system.

As suggested by Adeyemi (2011), funding challenges in education can be solved through revitalization strategies, intensification of generation of taxes, institution of bursaries, students' loans, and scholarships by governments at all levels. All these can be realized through improved allocation to the education sector. There is also the need to institute robust research endowment fund and enforce financial discipline in the sector. Moja (2000) submitted that education funding mechanisms in Nigeria must be rethought along the line of sustainable funding so that the country can attain her prime role as a critical player in the global order. Financial efficiency could be achieved in the sector through innovative managerial practices, rationalization, and pragmatic planning (Moja, 2000) as well as prioritization of projects. In relation to the development of nanotechnology in the country, there is the need to dedicate fund for the establishment of centres of excellence in nanotechnology with sophisticated equipment in some Nigerian universities, where researchers have shown competence in this field. The minimum that is required at the moment is to have functional regional nanoscience centres in the six geopolitical zones of the country. Similarly, information obtained from Table 1 on research grants for nanotechnology investigations showed that a lot more is needed to be done in making grants available to scholars in this field. These could be driven by governmental agencies, industries and public-spirited foundations and individuals. Furthermore, it should be one of the thematic areas that should be prioritized and generously funded under the national research fund of TETFund.

7.2 Curriculum development

Another problem in the pursuance of nanotechnology development in the country has to do with inadequacies in the curricula of subjects at high school level and courses in the higher institutions. Through effective curriculum development, the teeming learners can be exposed to issues on nanotechnology at the early part of their academic pursuits, thereby creating awareness and stimulating their interests in pursuing researches in nanotechnology. At the moment, the authors are not aware of any postgraduate programme in Nigerian universities that leads to the award of higher degrees in nanotechnology, nor there exist a Department of Nanoscience and Nanotechnology in any of the institutions. That which is obtainable is the pockets of research in disciplines of Pharmacy, Engineering and Life Sciences that are infused with some inputs from nanotechnology. There is therefore the need to reengineer curricula of science subjects at high school and those of courses in science, engineering, agriculture and medical sciences at higher institutions with contents of nanotechnology. Scholars can also infuse some concepts of nanotechnology in relevant courses. For instance, at our university, the lead author has incorporated nanobiotechnology in the contents of 'Introductory Biotechnology' at the final year in the degree programme of Pure and Applied Biology, with a lot of zeal to learn and enthusiasm by the students. A good number of these students have their final year projects executed in the field of nanobiotechnology with some outstanding outcomes. Through these, the curricula would have been brought in tandem with a realistic hope of repositioning science and technology in the country to meet the dynamic demands of the society.

7.3 Dearth of human resources and expertise

Shu'ara (2010) has reported a general shortage of teaching staff in all disciplines but more critical of science and technology disciplines in higher institutions in Nigeria (39.1 % shortage in Universities, and 56.9 % shortage in both Polytechnics and Colleges of education). The statistics would certainly be worse when considering the experts available to drive teaching and learning in nanotechnology. Other major challenges of nanotechnology development as reported by Alo (2013) includes; lack of appropriate law or regulatory structure, infrastructure and human capacity in the field, absence of private sector engagement in research and development, weak teamwork and networking among governmental agencies, lack of translational research institutes and industries to develop nano-based products, weak industrial base, inadequate foreign relationship especially with donors in the field of nanotechnology, concerns about possible adverse impacts of nanotechnology on health and environment, and safety risks. It is therefore expedient that resources should be mobilized to train experts in nanotechnology and promotion of multidisciplinary research should be encouraged to expand the applications of nanotechnology among different experts.

In this regard, regular organization of short training, workshops and conferences on nanotechnology would play prominent roles at training postgraduate students and early career scholars in the art of nanotechnology. Our multidisciplinary research group, Nano technology Research Group (*NANO+*, www.lautechnanotech.com), established in 2014 has provided leadership in this regard by organizing workshops and conference on nanotechnology in 2017 and 2018 at Ladoke Akintola University of Technology, Ogbomoso, Nigeria with remarkable successes at creating critical mass of scientists with expertise in nanotechnology. The third edition of her workshop/conference on nanotechnology is scheduled for 22-24 October 2019. Some of the papers presented at the 2018 edition are to be published in the flagship journal of the Faculty of Pure and Applied Sciences, '*Science Focus*', while the papers presented at the LAUTECH NANO 2019 conference would appear in '*IOP Conference Series: Materials Science and Engineering*'. Similar conferences focussing on nanotechnology are known to have been held at the University of Nigeria, Nsukka and Federal University, Oye-Ekiti.

We have also trained some postgraduate scholars in this field that have conducted investigations whose outcomes have appeared in very good international journals. These scholars have proficiencies in the green synthesis of MeNPs, their basic characterization and numerous applications. The activities of the group have also spurred several scientists to incorporate nanotechnology in their investigations, while colleagues have been mentored in some universities. Each higher institution in the country certainly needs a dialogue on nano technolo -gy research. The engagement on nanotechnology discourse should involve all sections of the society to resolve all the identified impediments and chart a course to develop the field. More importantly, the government should provide a national roadmap on nanotechnology development in the country. There is the need to revamp the Nigerian nanotechnology initiative (NNI) towards developing it into a full-fledge governmental agency for the coordination of activities on nanotechnology in Nigeria.

8.0 Prospects

The prospect of developing nanotechnology base for the country is huge in view of its multidisciplinary concept that seeks to create nanomaterials or improve existing products for applications in all facets of human endeavours. Globally, nanotechnology will play prominent roles in the development of robotic devices and expert systems, nanosensors, nano-electronics, diagnostic systems, functional materials for different applications, efficient solar cells, nanopharmaceuticals, hardware for security and defence systems, novel consumer products and nanomanufacturing amongst others. At the national level, Nigeria would benefit from nanotechnology in areas such as the provision of clean water, sustainable agriculture, food safety and security, quality healthcare, renewable energy, pollution control and environmental remediation. With necessary planning and execution through enactment of regulatory framework, improved funding of education, prioritization of nanotechnology research, training and manpower development, reengineering of curricula and intense sensitization of public and policymakers on nanotechnology-related issues, Nigeria is poised to play active roles in nanotechnology research and development for the benefits of her citizen and beyond. There is still a massive gap between what nanotechnology has capacity to deliver and what it has actually delivered so far as sophisticated nanoscale machines capable of operating with atomic precision have been imagined (Kallamu, 2013). Also, with the advances of nanotechnology in the field of medical sciences, it possesses a great advantage in finding lasting solutions to various health challenges especially those of physiological origin, cardiovascular diseases and combating the scourge of antimicrobial resistance prevalent in developing countries like Nigeria. Nanotechnological applications in agriculture should be taken with utmost seriousness to improve the economy from the area of crop and animal production. Therefore, there exist several target areas that Nigeria can benefit from by developing a national policy on nanotechnology research and development.

9.0 Conclusion

In this review, concerted efforts have been made to place in proper perspectives, the research landscape of green nanotechnology in Nigeria, and discussion of the factors that are responsible for the slow pace of investigations in Nigeria. For Nigeria to move up the ladder in the trend of nanotechnology research, the country must inject more funds into education, revamp the curricula and invest in the training of critical mass of specialists in the multidisciplinary field. There is also an urgent need to evolve a roadmap on nanotechnology for development in the country. A lot more can be achieved by the country through multilateral and bilateral cooperation with advanced countries in areas of manpower development, acquisition of state-of-the-art equipment and grants to fund nanotechnology research. With the ongoing developments in advanced nations, Nigerian universities, and research institutes should focus not just on synthesis of nanoparticles, but also nanophotonics, nanobiotechnology, nanocos metics, nanomedicine, nanoengineering, and simulation and modeling of nanostructures for diverse applications in rendering novel goods and services.

Table 1: Some activities of Nigerian universities in green nanotechnology

Type of Nanoparticles	Green material used for the synthesis	Applications	Nigerian Institution	International collaboration	*Funding	References
AgNPs	EPS of lactic acid bacteria	Antibacterial	University of Ibadan, Ibadan	-	-	Adebayo-Tayo, and Popoola (2017)
AgNPs	*Verbascum thapsus* extract	-	Federal University of Petroleum Resources (FUPRE), Effurum	North-West University, South Africa	-	Elemike *et al.* (2016b)
AgNPs	Cobweb extract	Desulfurization	Ladoke Akintola University of Technology (LAUTECH), Ogbomoso	-	-	Olajire *et al.* (2017d)
AgNPs	Sugarcane juice	Antibacterial	FUPRE, Effurum; & Federal University (FUL), Lafia.	-	-	Elemike *et al.* (2016a)
AgNPs	Honey	Anticorrosion	University of Uyo, Uyo	King Fahd University of Petroleum and Minerals, (KFUPM), Saudi Arabia	TWAS, Italy	Obot *et al.* (2013)
AgNPs	Leaf extract of *Detarium microcarpum*	Antioxidant, & detection of heavy metals	FUL, Lafia; Federal University, Oye-Ekiti; Federal University of Agriculture, Abeokuta (FUNAAB); & University of Ibadan, Ibadan	University of KwaZulu-Natal (UKZN), South Africa	-	Labulo *et al.* (2016b)
AgNPs	Leaf extract of *Ananas comosus*	Antibacterial	FUL, Lafia; & FUNAAB, Abeokuta	-	-	Elemike *et al.* (2014)
AgNPs	Leaf extracts of several plants	-	FUL, Lafia; FUNAAB, Abeokuta; & FUPRE, Effurum	Florida State University, USA	-	Dare *et al.* (2015)
AgNPs	Root extracts of *Waltheria americana*	Antibacterial	Modibbo Adama University of Technology, Yola; & FUL, Lafia	-	-	Deshi *et al.* (2016)
AgNPs	Root extracts of black carrot	-	Federal University, Dutse	Lovely Professional University, India; Amity Institute of Nanotechnology, India; & Punjab University, India	-	Abubakar *et al.* (2014)
AgNPs	Aqueous leaf extract of *Eupatorium odoratum*	Antimicrobial & larvicidal	FUPRE, Effurun; & Federal University (FUNAI), Ndufu-Alike Ikwo	North-West University, South Africa	-	Elemike *et al.* (2017e)

AgNPs	Leaf extracts of *Parquetina nigrescens* & *Synedrella nodiflora*	Antimicrobial	University of Ibadan, Ibadan; & FUL, Lafia	-	-	Ogunsile *et al.* (2016)
AgNPs	Seed extracts of *Cyperus esculentus* & *Butyrospermum paradoxum*	Antimicrobial	University of Ibadan, Ibadan	-	-	Ajayi *et al.* (2015)
AgNPs	Leaf extract of *Artemisia annua* & *Sida acuta*	Antimicrobial, Antioxidant & anticorrosion	University of Uyo, Uyo	KFUPM, Saudi Arabia	TWAS	Johnso *et al.* (2014)
AgNPs	Leaf extracts of *Canna indica* & *Senna occidentalis*	-	Covenant University, Ota; & FUNAAB, Abeokuta	University of Johannesburg, South Africa	-	Akinsiku *et al.,* (2015)
AgNPs	Leaf extracts of *Cassia hirsute*	Larvicidal	FUL, Lafia; & University of Ilorin	UKZN, South Africa	-	Adesuyi *et al.* (2016)
AgNPs	Crude keratinase of *Bacillus safensis*	Antibacterial	LAUTECH, Ogbomoso; & Federal University of Technology (FUT), Minna	UKZN, South Africa	TETFund	Lateef *et al.* (2015a)
AgNPs	Crude laccase of *Lentinus edodes*	Antibacterial	LAUTECH, Ogbomoso	-	-	Lateef and Adeeyo (2015)
AgNPs	Pod extract of *Cola nitida*	Enhancement of antioxidant properties of *Amaranthus*	Osun State University (UNIOSUN), Osogbo; & LAUTECH, Ogbomoso	-	-	Azeez *et al.* (2017a)
AgNPs	Cell-free extract of *Bacillus safensis* LAU 13	Antibacterial, Antifungal, paint additive Antioxidant, & larvicidal	LAUTECH, Ogbomoso; & UNIOSUN, Osogbo	UKZN, South Africa	-	Lateef *et al.* (2015d)
AgNPs	Cell-free extract of *Bacillus safensis* LAU 13	Anti-candida, Anticoagulant & thrombolytic	LAUTECH, Ogbomoso	-	-	Lateef *et al.* (2016e)
AgNPs	Cobweb extract	Antibacterial, & Paint additive	LAUTECH, Ogbomoso	UKZN, South Africa	-	Lateef *et al.* (2016d)
AgNPs	Cocoa bean extract	Antibacterial, Paint additive, larvicidal, & anticoagulant	LAUTECH, Ogbomoso	UKZN, South Africa	-	Azeez *et al.* (2017)
AgNPs	Nest extract of paper wasp (*Polistes* spp.)	Antimicrobial, catalytic, anticoagulant, & thrombolytic	LAUTECH, Ogbomoso	UKZN, South Africa	-	Lateef *et al.* (2017c)
AgNPs	Spider cobweb, Pod, seed & seed shell of *C. nitida*	Antioxidant, anticoagulant, & thrombolytic	LAUTECH, Ogbomoso	-	-	Lateef *et al.* (2017)
AgNPs	Leaf extract of *Petiveria alliacea*	Antimicrobial, antioxidant, & anticoagulant	LAUTECH, Ogbomoso	UKZN, South Africa	-	Lateef *et al.* (2018b)
AgNPs	Pod extract of *C. nitida*	Antibacterial, Antioxidant & Paint additive	LAUTECH, Ogbomoso; & UNIOSUN, Osogbo	UKZN, South Africa	-	Lateef *et al.* (2016b)

AgNPs	Seed and seed shell extracts of *C. nitida*	Antibacterial	LAUTECH, Ogbomoso	UKZN, South Africa	-	Lateef *et al.* (2015e)
AgNPs	Cocoa pod husk extract	Antimicrobial, antibiotic synergistic, antioxidant, & larvicidal	LAUTECH, Ogbomoso; UNIOSUN Osogbo	UKZN, South Africa	-	Lateef *et al.* (2016f)
AgNPs	Seed extract of *Buchholzia coriacea*	antimicrobial	FUT, Minna; & LAUTECH, Ogbomoso	-	-	Adelere *et al.* (2017)
AgNPs	Xylanases of *Aspergillus niger* & *Trichoderma longibrachiatum*	Antimicrobial, catalytic, antioxidant, anticoagulant, & thrombolytic		UKZN, South Africa	-	Elegbede *et al.* (2018a)
AgNPs	Stem extract of *Chasmanthera dependens*	Antimicrobial, antioxidant, anticoagulant, thrombolytic & larvicidal	Babcock University, Ilishan-Remo; LAUTECH, Ogbomoso; Federal University (FUOYE), Oye-Ekiti; & Redeemer's University, Ede	KFUPM, Saudi Arabia	-	Aina *et al.* (2019)
AgNPs	Extract of cocoa pod	Modulation of plant growth, pathogen suppression & antioxidant stimulation	UNIOSUN, Osogbo; & LAUTECH, Ogbomoso	-	-	Azeez *et al.* (2019a)
AgNPs	Extract of cocoa bean	Osmotic dehydration, pathogen suppression & antioxidant stimulation	UNIOSUN, Osogbo; & LAUTECH, Ogbomoso	-	-	Azeez *et al.* (2019b)
AgNPs	Extract of cocoa pod	Modulation of plant growth, immobilization of toxic metals & antioxidant stimulation	UNIOSUN, Osogbo; LAUTECH, Ogbomoso; & FUOYE, Oye-Ekiti	-	-	Azeez *et al.* (2019c)
AgNPs	Banana trunk fibres	-	Federal University of Technology (FUTO), Owerri	Bronx City College, USA.	-	Akolade *et al.* (2012)
AgNPs	Aqueous leaf extract of *Lippia citriodora*.	Antimicrobial; larvicidal; & photocatalysis	FUPRE, Effurun; FUNAI, Ndufu-Alike Ikwo; & Ebonyi State University, Abakaliki	North-West University, South Africa	-	Elemike *et al.* (2017f)
AgNPs	*Lasienthra africanum* leaf extract	-	FUPRE, Effurun	North-West University, South Africa	-	Elemike *et al.* (2017a)
AgNPs	Leaf extract of *Azadirachta indica*	Application against yam rot micro organisms	University of Nigeria (UNN), Nsukka; & Enugu State University, Enugu	-	-	Eze *et al.* (2016a)
AgNPs	Leaf extract of *Azadirachta indica*	Controlling postharvest	UNN, Nsukka	-	-	Eze *et al.* (2016b)

		losses of fresh yam tuber				
AgNPs	Brands of beer	-	FUL, Lafia	-	-	Adesuji *et al.* (2013)
AgNPs	*Costus afer* leaf extract	Antibacterial, antioxidant & Electrochemical	FUPRE, Effurun; FUNAI, Ndufu-Alike Ikwo; & Ebonyi State University, Abakaliki	North-West University, South Africa	-	Elemike *et al.* (2017d)
AgNPs	Extracts of cobweb and seed shell of *Cola nitida*	Desulfurization	LAUTECH, Ogbomoso; Afe Babalola University, Ado-Ekiti; & Covenant University, Ota	UKZN, South Africa	-	[130]
AgNPs	Aqueous leaf extract of *Lavandula × intermedia*	Antimicrobial	FUPRE, Effurun; & FUNAI, Ndufu-Alike Ikwo	North-West University, South Africa		Olajire *et al.* (2017d)
AgNPs	Leaf extract of *Talinum triangulare*	Antimicrobial antioxidant, & electrochemical activities	FUPRE, Effurun; & FUNAI, Ndufu-Alike Ikwo	North-West University, South Africa	-	Elemike *et al.* (2017c)
AgNPs	Hydrosol extract of *Acacia mearnsii*	Anti-inflammatory	Lagos State University, Ojo	University of Fort Hare, Alice, South Africa; Walter Sisulu University, Mthatha, South Africa; University of Zululand, South Africa; & University of Johannesburg, Johannesburg,	National Research Foundation (NRF), South Africa.	Avoseh *et al.* (2017)
AgNPs	Leaf extract of *Thevetia peruviana*	Antimicrobial	University of Ilorin, Ilorin	UKZN, South Africa	-	Oluwaniyi *et al.*(2016)
AgNPs	Aqueous extract *Garcinia kola*	Antimicrobial	FUL, Lafia; Federal FUNAAB, Abeokuta; & Covenant University, Ota	UKZN, South Africa	-	Labulo *et al.* (2016a)
AgNPs	Leaf extract of *Syzygium cumini*	Antimicrobial	Afe Babalola University, Ado-Ekiti	-	-	Ojo *et al.* (2018)
AgNPs	Leaf extracts of *Vernonia amygdalina, Telferia occidentalis* & *Lasianthera africana*	Antimicrobial	University of Uyo, Uyo	-	TETFund	Jackson *et al.* (2018a)
AgNPs	Fruit juices of *Citrus* sp	Antimicrobial	University of Uyo, Uyo	-	TETFund	Jackson *et al.* (2018b)
AgNPs	Leaf extract of *Carica papaya*	Antimicrobial	University of Uyo, Uyo	-	TETFund	Jackson *et al.* (2018c)
AgNPs	Leaf extract of *Tithonia diversifolia*	Antimicrobial	Landmark University, Omu-Aran; Federal University Dutsin-	The University of Mississippi, USA	-	Dada *et al.* (2018)

			Ma, Dutsin-Ma; & Nigerian Stored Product Research Institute (NSPRI), Ilorin			
AgNPs	Fresh and fermented palm wine	Antimicrobial	FUPRE, Effurun; & Kogi State Polytechnic, Lokoja	North-West University, South Africa		Elemike *et al.* (2018a)
AgNPs	Leaf extract of *Artemisia afra*	Antimicrobial & antioxidant	FUPRE, Effurun; & FUNAI, Ndufu-Alike Ikwo	North-West University, South Africa	-	Elemike *et al.* (2018b)
AgNPs	Flower extract of *Tagetes patula*	-	FUPRE, Effurun	North-West University, South Africa	-	Elemike *et al.* (2018c)
AgNPs	Cell-free extract of *Bacillus subtilis*	Antimicrobial	University of Port-Harcourt, Port-Harcourt	Rhodes University, Grahamstown, South Africa	-	Maduabuchi *et al.* (2018)
AgNPs	*Kigelia africana* fruit extract	Antimicrobial	University of Calabar, Calabar; & FUL, Lafia	-	TWAS, & Royal Society of Chemistry (UK)	Ashishie *et al.* (2018)
AgNPs	Leaf extract of *Tectona grandis*	Antimicrobial	Covenant University, Ota	Tswhane University of Technology, Pretoria, South Africa; & Vaal University of Technology, South Africa	NRF-TWAS; & Covenant University, Ota	Okeniyi *et al.* (2018)
AgNPs	Bark extract of *Albizia chevalier*	Antimicrobial, anticancer; & catalytic	Federal University, Dutse	University of Swabi, Anbar, Pakistan; King Abdul-Aziz University, Jeddah, Saudi Arabia; & Shaheed Benazir Bhutto Women University, Pakistan		Khan *et al.* (2018)
AgNPs	*Laportea aestuans* leaf extract	Antimicrobial	Adekunle Ajasin University, Akungba-Akoko	-	-	Bankole (2018)
AgNPs	*Jatropha curcas* seed oil	Antimicrobial	Bayero University, Kano; & Federal University, Dutsin-Ma	-	-	Musa and Abubakar (2019)
AgNPs	*Callistemon citrinus* extract	Antimicrobial antimalaria, & antitrypanosoma	Kogi State University, Anyigba	University of Fort Hare, Alice, South Africa	Kogi State University, Anyigba	Larayetan *et al.* (2019a)
AgNPs; AuNPs; PdNPs	Aqueous leaf extract of *Basella alba*	-	FUOYE, Oye-Ekiti; & FUNAAB, Abeokuta	University of Zululand, South Africa	NRF, South Africa	Sodeinde *et al.* (2016a)
AgNPs; AuNPs; Ag-AuNPs	Aqueous extract of *Chrysophyllum albidum*	Catalytic application	FUOYE, Oye-Ekiti; & FUNAAB, Abeokuta	University of Johannesburg, South Africa; & University of Zululand, South Africa	Department of Science and Technology (DST); & NRF, South Africa	Sodeinde *et al.* (2016b)

Silver nanocolloid	*A. conyzoides* L. plant extract	-	Adamawa State University, Mubi; & Modibbo Adama University of Technology, Yola	-	-	Barminas *et al.* (2014)
AuNPs	*Nauclea latifolia* leaf/plant extract	-	African University of Science and Technology AUST), Abuja; & Kwara State University (KWASU), Malete	Princeton University, USA; Bronx Community College, USA; & Princeton Institute for the Science and Technology of Materials (PRISM), USA	-	Dozie-Nwachukwu *et al.* (2016a)
AuNPs	Leaf extract of *Nelsonia canescens*	*In vivo* membranous activity	FUT, Minna	-	TETFund	Shittu and Stephen (2017)
AuNPs	Aqueous leaf extract of *Calotropis procera*	Anticancer	FUT, Minna	-	TETFund	Shittu and Stephen (2016)
AuNPs	*Nauclea latifolia* leaf/plant extract	Cancer detection and treatment	AUST, Abuja; & KWASU, Malete	Princeton University, USA; Bronx Community College, USA; PRISM, USA; & Massachusetts Institute of Technology	-	Oni *et al.* (2016)
AuNPs	*Bacillus megaterium*	Detection and treatment of breast cancer cells	AUST, Abuja	PRISM, USA; & Bronx Community College, USA	Princeton University, USA; African Development Bank (AfDP); & World Bank	Hampp *et al.* (2012)
AuNPs	Cell-free extract and biomass of *Serratia marcescens*	-	AUST, Abuja,	PRISM, USA	World Bank	Dozie-Nwachukwu *et al.* (2016b)
AuNPs	Leaf extracts of *Gomphrena celosioides* & *Prunus amygdalus*	Antibacterial	FUT, Minna; Ibrahim Badamasi Babangida University, Lapai	-	TETFund	Abalaka *et al.* (2014)
AuNPs	Cell-free extract of *Bacillus safensis* LAU 13	Antifungal Anticoagulant & thrombolytic	LAUTECH, Ogbomoso; & Oyo State College of Agriculture & Science, Igboora	UKZN, South Africa.	-	Ojo *et al.* (2016)
AuNPs	Cell-free extracts of four strains of non-pathogenic *Enterococcus* species	Anticoagulant, thrombolytic, Antioxidant & Larvicidal	LAUTECH, Ogbomoso	UKZN, South Africa.	-	Oladipo *et al.* (2017a)
AuNPs	Xylanases of *Aspergillus niger* & *Trichoderma longibrachiatum*	Antimicrobial, antioxidant, anticoagulant, & thrombolytic	LAUTECH, Ogbomoso; & Babcock University, Ilishan-Remo	UKZN, South Africa.	-	Elegbede *et al.* (2018b)

AuNPs	Palm oil leaf extract	-	Federal University, Kashere	University Sains Malaysia, Pulau Pinang, Malaysia	-	Usman *et al.* (2019)
AuNPs	Seed extract of *Callistemon citrinus*	Antimalarial, antitrypanocidal and antimicrobial	Kogi State University, Anyigba	University of Fort Hare, Alice, South Africa	Kogi State University, Anyigba	Larayetan *et al.* (2019b)
AuNPs	EPS and metabolites of *Wesiella confusa*	Antibacterial	University of Ibadan	Prince Mohammad Bin Fahd University, Al Khobar, Saudi Arabia	-	Adebayo-Tayo *et al.* (2019)
AuNPs	Leaf extract of *Catharanthus roseus*	Antimicrobial	FUT, Minna	Baylor College of Medicine Bates, Houston, Texas	-	Shittu *et al.* (2017a)
Gold/prodigiosin	Prodigiosin extracted from *Serratia marcescens*	-	AUST, Abuja, Nigeria	PRISM, USA	World Bank	Dozie-Nwachukwu *et al.* (2017a)
Ag-AuNPs	Cell-free extract of *Bacillus safensis* LAU 13	Antifungal anticoagulant, thrombolytic, & catalytic	LAUTECH, Ogbomoso; & Oyo State College of Agriculture and Science, Igboora	UKZN, South Africa.	-	Ojo *et al.* (2016)
Ag-AuNPs	Leaf, seed, seed shell and pod extracts of *Cola nitida*	Antifungal anticoagulant, thrombolytic, catalytic, & larvicidal	LAUTECH, Ogbomoso	UKZN, South Africa.	-	Dozie-Nwachukwu *et al.* (2016b)
Ag-AuNPs	Xylanases of *Aspergillus niger* & *Trichoderma longibrachiatum*	Antimicrobial, antioxidant, anticoagulant, & thrombolytic	LAUTECH, Ogbomoso	UKZN, South Africa; KFUPM, Saudi Arabia	-	Elegbede *et al.* (2019)
Au@PtNPs	*Carica papaya* leaf extract	Desulfurization	LAUTECH, Ogbomoso	-	-	Olajire and Adesina (2017)
Tungsten trioxide (WO_3) nanoparticles	*Spondias mombin* aqueous leaf extract	-	FUT, Minna	University of the Free State, South Africa	TETFund	Tijani *et al.* (2019)
Nickel nanoparticles	*Moringa oleifera* leaf extract	Electron transfer	Adamawa State University, Mubi; & Federal College of Education (Technical), Gombe	-	TETFund	Mamuru and Jaji (2015)
Chromium and nickel nanoparticles	*Annona squamosa* leaf extract	-	Adamawa State University, Mubi	-	TETFund	Mamuru *et al.* (2015)
Starch stabilized Magnetic nanoparticles (SSMNPs)	Starch solution	Adsorbents for removal of Ni (II), Co (II) & Pb (II) ions	Rivers State University of Science and Technology, Port Harcourt	-	-	Konne *et al.* (2015)
Starch stabilized Magnetic nanoparticles (SSMNPs)	Cassava waste water starch solution	Bioremediation	Rivers State University of Science and Technology, Port Harcourt	-	-	Konne and Okpara (2014)
Magnetite nanoparticles	*Magnetospirillum magneticum*	Targeting and treatment of breast cancer	AUST, Abuja; KWASU, Malete; & Nigerian Turkish Nile University, Abuja	Bronx Community College, Bronx, New York; PRISM, USA;	World Bank; & African Development Bank (AfDB)	Obayemi *et al.* (2015)

				Rutgers University, USA; & National University of Singapore, Singapore		
Chitosan-Magnetite nanoparticles (CS-MNPs)	Chitosan	Drug delivery	FUNAAB, Abeokuta; Tai-Solarin University of Education, Ijagun; & Obafemi Awolowo University, Ile-Ife	-	-	Akinsipo *et al.* (2016b)
FeNPs	Extract of mango leaves	Dye degradation	Tai Solarin University of Education, Ijagun; & Obafemi Awolowo University, Ile-Ife	-	-	Akinsipo *et al.* (2016a)
FeNPs	Peel extract of *Musa sapientum*	Anticorrosion	University of Uyo, Uyo	-	-	Ituen *et al.* (2019)
ZnNPs	Leaf extract of *Dialium guineense*	Antimicrobial	Covenant University, Ota	-	-	Okeniyi *et al.* (2017)
ZnONPs	*Citrus sinensis*	Deposition of zinc on mild steel	Covenant University, Ota	-	-	Ajayi *et al.* (2018)
ZnONPs	*Ocimum gratissimum* & *Vernonia amygdalina* leaf extracts	Growth of *Amaranthus cruentus*	Federal University of agriculture, Makurdi; FUL, Lafia	University of Bristol, UK	TETFund	Mfon *et al.* (2017)
ZnONPs	Plantain peel extract	-	Rivers State University, Port-Harcourt	-	-	Onubun *et al.* (2017)
ZnONPs	Extracts of olive leaves (*Olea europaea*), chamomile flower (*Matricaria chamomilla*), & red tomato fruit (*Lycopersicon esculentum*	Antibacterial	FUNAAB, Abeokuta	Zhejiang University, Hangzhou, PR China; & Plant Protection Research Institute, Agricultural Research Center, Cairo, Egypt	Zhejiang Provincial Natural Science Foundation of China; National Natural Science Foundation of China; Zhejiang Provincial Project; National Key Research and Development Program of China; Shanghai Agricultural Basic Research Project & Key Scientific Technological Project of Ningbo	Ogunyemi *et al.* (2019)

ZnONPs	Leaf extract of *Amaranthus spinosus*	Antimicrobial	First Technical University, Ibadan; Bingham University, Karu; Obafemi Awolowo University, Ile-Ife; FUOYE, Oye-Ekiti; Lead City University, Ibadan; & Mountain Top University, Prayer city	-	-	Alayande *et al.* (2019)
ZnSe	Ascorbic acid	-	Olabisi Onabanjo University, Ago-Iwoye	Walter Sisulu University, South Africa; & University of South Africa	NRF, South Africa	Oluwafemi *et al.* (2010)
ZnSe	Starch	-	Olabisi Onabanjo University, Ago-Iwoye	Walter Sisulu University, South Africa; & University of South Africa	NRF, South Africa	Oluwafemi and Adeyemi (2010)
CdSe nanostructures	Starch	-	Olabisi Onabanjo University, Ago-Iwoye	University of Zululand, South Africa; & Nelson Mandela Metropolitan University, South Africa	NRF, South Africa	Oluwafemi (2009)
CdSe and ZnSe	Cysteine, ascorbic acid and starch	-	Olabisi Onabanjo University, Ago-Iwoye	University of Zululand, South Africa	CSIR, South Africa; & NRF, South Africa	Oluwafemi and Revaprasadu (2008)
TiO_2	*Hibiscus sabdariffa* & *Azardirachta indica* calyxes	Photovoltaic applications	Lagos State University, Ojo; Fountain University, Osogbo & University of Lagos, Lagos	-	-	Boyo *et al.* (2013)
TiO_2	Natural dyes extracted from the bark of *Lawsonia inermis*	Dye sensitized solar cells (DSSC)	Lagos State University, Ojo; University of Lagos, Lagos; & Fountain University, Osogbo	-	-	Boyo *et al.* (2012)
TiO_2	Natural dye extracts from *Hibiscus sabdariffa*	Dye sensitized solar cells (DSSC)	Ahmadu Bello University, Zaria	-	-	Ahmed *et al.* (2013)
FTO/TiO_2/AgNPs (Dye sensitized solar cells)	*Hibiscus sabdariffa* dye	Photovoltaic	Nigeria Defence Academy, Kaduna; & Kaduna State University, Kaduna	-	-	Eli *et al.* (2016b)
FTO/TiO_2/AgNPs (Dye sensitized solar cells)	*Carica papaya* dye	Photovoltaic performance	Nigeria Defence Academy, Kaduna	-	-	Eli *et al.* (2016a)
Carbon nanoparticles	*Citrus sinensis* Peel	Sorbent for pollutant dyes	LAUTECH, Ogbomoso	CSIR-Central Glass and	TWAS-CSIR	Adedokun *et al.* (2017)

				Ceramic Research Institute, India		
Platinum nanoparticles (PtNPs)	Aqueous bark extract of *Alchornea laxiflora*	Desulfurization of model oil	LAUTECH, Ogbomoso	UKZN, South Africa	-	Olajire *et al.* (2017a)
Pt@Cu nanostructures	*A. laxiflora* leaf extract	Catalytic oxidation of oil	LAUTECH, Ogbomoso	UKZN, South Africa	-	Olajire *et al.* (2017b)
CuNPs	*A. laxiflora* leaf extract	Catalytic oxidation of oil	LAUTECH, Ogbomoso; & Covenant University, Ota	UKZN, South Africa	-	Olajire *et al.* (2018)

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Author's contribution

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