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A REVIEW OF BIOMEDICAL APPLICATIONS OF NANOMATERIALS AMONGST AFRICAN RESEARCHERS

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ABSTRACT
Nanotechnology is gaining much interest worldwide because of its enormous applications in almost all spheres of life such as in medicine, agriculture, energy, engineering and other unexploited areas of human endeavors. However, the development of nanotechnology in Africa is still nascent as most African researchers are just beginning to welcome and accept this new area of research, although some ground breaking nanotechnology based discoveries are beginning to emerge. This review aims at examining biomedical applications of nanomaterials amongst African researchers to help determine the extent to which nanomaterials have been harness in biomedicine and proffer appropriate recommendations for improvement.

Keywords: *African Researchers; Application; Biomedical; Nanomaterials; Nanotechnology*.

INTRODUCTION
Nanotechnology is fast becoming the order of the day in most developed countries around the world. So many fields including; medicine, engineering, agriculture, energy and defense have embraced this advancement in technology. This has also opened up new areas of research interest all over the globe. Despite this advancement, the African continent lags behind other continents. However, some researchers in Africa are beginning to welcome and accept this novel concept and have carried out ground breaking discoveries. Nanotechnology is transforming and revolutionizing different fields around the globe especially in countries which have embraced it long ago. Nanomaterials have also shown great importance as researchers gradually unravels the diverse gains of nanotechnology.[1]

The biomedical sector seems to be lagging behind compared to other sectors. Having a sound knowledge of what African researcher have done so far will arouse the interest of young Africans scientists who want to delve into nanotechnology as well as inform the government of appropriate strategies that can be explored to uplift Africa to be at par with other advanced countries. This article reviews the biomedical applications of nanomaterials in North, South, East and West Africa.

METHOD
DATA COLLECTION
The databases used in this review were Google scholar, PubMed, Science Direct and Crossref. Also, other resources such as Wiley online library, research for life etc. were also used. The inclusion criteria were based on direct link of research to biomedical application of nanomaterials which involves at least one African researcher. The search word used are 'nanotechnology in Africa', 'nanomaterial application in Africa', 'biomedical uses of nanomaterials in Africa', 'African researchers and nanomaterials', 'use of nanomaterials amongst African researchers', 'nano-technological advances in Africa', 'advances in medical diagnosis and treatments using nanomaterials', 'synthesis of nanoparticles in Africa', 'application of nanoparticles' and 'metal nanoparticles used in Africa'.

On the exclusion criteria, articles not related to the biomedical application of nanomaterials by African researchers were excluded. Publications earlier than 2000, biomedical application of nanomaterial not involving any African researcher, non-biomedical applications of nanomaterials, biomedical researches not involving the use of nanomaterials as well as articles not published in English language were all excluded from this review.

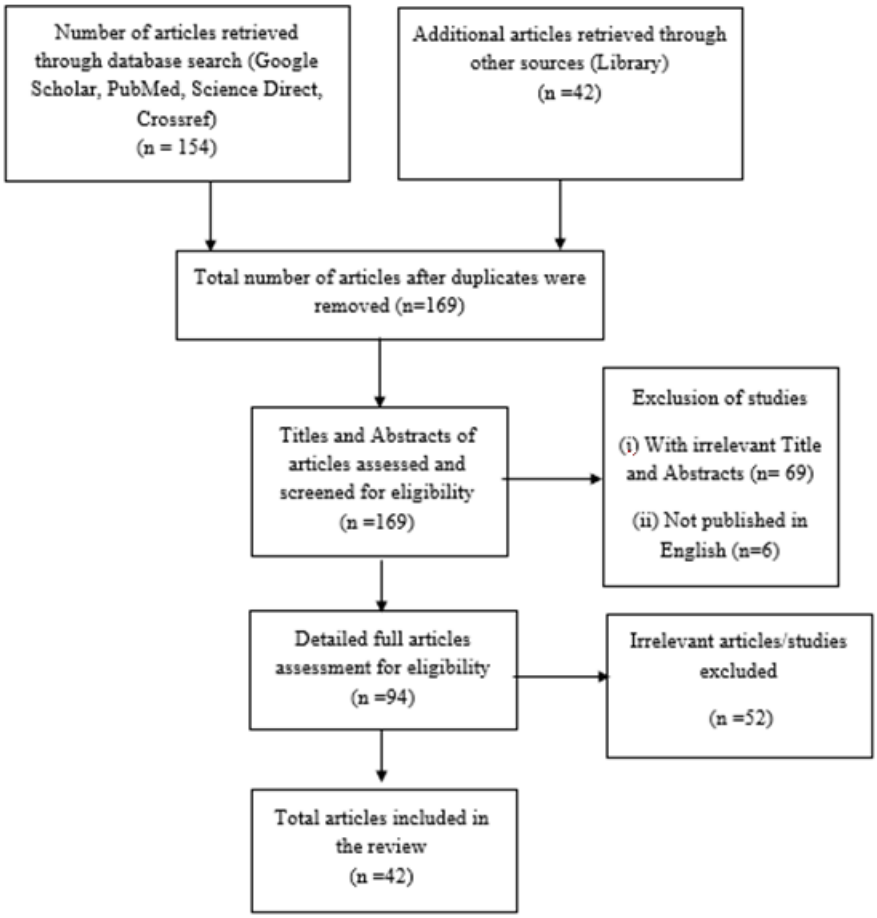

Fig 1: Article screening flow chart (PRISMA).

RESULT AND DISCUSSION

Table 1: Biomedical applications of Nanomaterials by African researchers.

TYPES OF NANOMATERIALS	MATERIALS USED FOR SYNTHESIS OF NANOMATERIAL	APPLICATION OF NANOMATERIAL	INSTITUTION/ COLLABORATIONS	FUNDING	REFERENCES
Silver	3mM silver nitrate solution + extract of *Cleome viscosa*	Antimicrobial activity	Department of Basic Medical Sciences, Asmara College of Health Sciences, Asmara, Eritrea, North East Africa.	Self-funded	Yamini *et al.*, 2011 [2]
Gold		Nano-biosensor for potential diagnosis of bilharzia antigen.	University of Kenya	Grand Challenges Canada (GCC) grant number 0426-01 and the Third World Academy of Sciences (TWAS) grant number 13-115 RG/CHE/AF/AC_I.	Naumih *et al.*, 2018 [3]
Silver	silver nitrate and the aqueous extract of *Citrullus lanatus* fruit rind	Antibacterial	Kenyatta University United States International University Africa, University of Kenya	Self-funded	Ndikau *et al.*, 2017 [4]
Silver	Silver nitrate and *Afzelia quanzensis* bark extract.	Antibacterial activity	Department of Chemical Technology, Faculty of Science, Zimbabwe	Self-funded	Mambo *et al.*, 2015 [5]

liposomes, nanoparticles, vector peptides and amino acids	-	Nanocarriers	Haramaya University, Haramaya, Ethiopia Addis Ababa University, Addis Ababa, Ethiopia	-	Migbaru *et al.*, 2016 [6]
Zinc Oxide	Zinc nitrate + Gigantic Swallow Wort leaves		Brindavan Institute of Technology & Science, and EIT, Mai-Nefhi, Asmara, Eritrea	-	Pankaj *et al.*, 2015 [7]
Organic and Inorganic nanoparticles		Dental Medicine: Dental Prevention and prophylaxis Dental Therapy Dental Restoration Dental Diagnosis	International University of Rabat, International Faculty of Dentistry, Sala Al Jadida, Morocco.	Self	Lbounne *et al.*, 2017 [8]
Inorganic nanoparticles (AuNPs)		*Mycobacterium Tuberculosis* Detection	American University, Cairo and Misr University for Science and Technology, Egypt	Grant from YJ-STRC and Qatar National Research Funds.	Hussain *et al.*, 2013 [9]
Inorganic nanoparticles and Organic nanoparticles		Nanocarriers for Drug Delivery	National Research Centre, Egypt. International and inter-University Centre for Nanoscience and Nanotechnology. India. Faculty of Science, Al-Azhar University, Cairo. Faculty of Engineering, Badr University, Cairo, Egypt. Department of Chemical Engineering, Loughborough University, UK	DST-Inspire Fellowship, Department of Science and Technology, New Delhi	Mabrouk *et al.*, 2019 [10]
Inorganic Nanoparticles		Drug Delivery	-	Self	Elzoghby, A. O., 2019 [11]
Inorganic Nanoparticles and Carbon-based nanoparticles		Antimicrobial agent Diagnosis Bio censors Antibiofilm Anticancer	Toyohashi University of Technology, Egyptian Atomic Energy Authority.	Nanotechnology Research Unit, Egypt	Elkodous *et al.*, 2019(a) [12]
Inorganic Nanoparticles (Ag NPs)		Cancer Treatment Potential HIV treatment	Nanotechnology Research Unit, Drug Microbiology Lab., Drug Radiation Research Department, NCRRT, Egypt	Nanotechnology Research Unit, Drug Microbiology Lab., Drug Radiation Research Department, NCRRT, Egypt	Elkodous *et al.*, 2019(b) [13]
AgNPs	EPS of lactic acid bacteria	Antibacterial	University of Ibadan, Ibadan	-	Adebayo-Tayo, *et al.*, 2017 [14]
AgNPs	*Verbascum thapsus* extract	-	Federal University of Petroleum Resources (FUPRE), Effurun/North-West University, South Africa	-	Elemike *et al.* 2016(b) [15]
AgNPs	Cobweb extract	Desulfurization	Ladoke Akintola University of	-	Olajire *et al.* 2017(d) [16]

			Technology (LAUTECH), Ogbomoso		
AgNPs	Sugarcane juice	Antibacterial	FUPRE, Effurun; & Federal University (FUL), Lafia.	-	Elemike *et al.* 2016(a) [17]
AgNPs	Honey	Anticorrosion	University of Uyo, Uyo/ King Fahd University of Petroleum and Minerals, (KFUPM), Saudi Arabia	TWAS, Italy	Obot *et al.*, 2013 [18]
AgNPs	Leaf extract of *Detarium microcarpum*	Antioxidant, & detection of heavy metals	Federal University, 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.*, 2016(b) [19]
AgNPs	Leaf extract of *Ananas comosus*	Antibacterial	Federal University, Lafia; & FUNAAB, Abeokuta	-	Elemike *et al.*, 2014 [20]
AgNPs	Leaf extracts of *several* plants	-	Federal University Lafia; FUNAAB, Abeokuta; & FUPRE, Effurun/Florida State University, USA	-	Dare *et al.*, 2015 [21]
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 [22]
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.* 2016(b) [23]
Ag-AuNPs	Xylanases of *Aspergillus niger* & *Trichoderma longibrachiatum*	Antimicrobial, antioxidant, anticoagulant, & thrombolytic	LAUTECH, Ogbomoso/ UKZN, South Africa; KFUPM, Saudi Arabia	-	Elegbede *et al.*, 2019 [24]
AuPtNPs	*Carica papaya* leaf extract	Desulfurization	LAUTECH, Ogbomoso	-	Olajire and Adesina 2017 [25]
Tungsten trioxide (WO_3) nanoparticles	*Spondias mombin* aqueous leaf extract	-	FUT, Minna/ University of the Free State, South Africa	TETFund	Tijani *et al.*, 2019 [26]

Nickel nanoparticles	*Moringa oleifera* leaf extract	Electron transfer	Adamawa State University, Mubi; & Federal College of Education (Technical), Gombe	TETFund	Mamuru and Jaji 2015 [27]
Chromium and nickel nanoparticles	*Annona squamosa* leaf extract	-	Adamawa State University, Mubi	TETFund	Mamuru *et al.*, 2015 [28]
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 [29]
Starch stabilized Magnetic nanoparticles (SSMNPs)	Cassava waste water starch solution	Bioremediation	Rivers State University of Science and Technology, Port Harcourt	-	Konne and Okpara 2014 [30]
Magnetite nanoparticles	*Magnetospirillum magneticum*	Targeting and treatment of breast cancer	AUST, Abuja; KWASU, Malete; & Nigerian Turkish Nile University, Abuja	World Bank; & African Development Bank (AfDB)	Obayemi *et al.*, 2015 [31]
Chitosan Magnetite nanoparticles (CS-MNPs)	Chitosan	Drug delivery	FUNAAB, Abeokuta; Tai- Solarin University of Education, Ijagun; & Obafemi Awolowo University, Ile-Ife	-	Akinsipo *et al.*, 2016(b) [32]
ZnNPs	Leaf extract of Dialium *guineense*	Antimicrobial	Covenant University, Ota	-	Okeniyi *et al.*, 2017 [33]
ZnONPs	Plantain peel extract	-	Rivers State University, Port Harcourt	-	Onubun *et al.*, 2017 [34]
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 Centre, 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	Ogunyemi *et al.*, 2019 [35]

				Research Project & Key Scientific Technological Project of Ningbo	
Poly Caprolactone-Efavirenz nanoparticles es	Polycaprolactone, Ethyl acetate, Dichloromethane, Efavirenz, Polyvinyl alcohol, lactose, trehalose, ultra-purified water	Improved HIV treatment	CSIR, University of Johannesburg South Africa	CSIR, South African Department of Science and technology	Katata *et al.*, 2012 [36]
Poly Caprolactone-Efavirenz nanoparticles es	Poly Caprolactone, polyvinyl alcohol, Ethyl acetate, Dichloromethane, Lactose monohydrate, trehalose (anhydrous), ultra-purified water	Improved HIV treatment	CSIR, North West University, Nelson Mandela African Institute of Science and Technology Tanzania	South Africa National Research Foundation	Tshweu *et al.*, 2013 [37]
PLGA Nanoparticles	Rifampicin, Isoniazid, Pyrazinamide, PLGA (50:50), Polyvinyl alcohol, Poly ethylene glycol, Lactose monohydrate, Chitosan (85% deacetylated), Glycerol, Tween 20, Pluronic F127, Phosphate buffered saline	Controlled drug release in the treatment of tuberculosis	CSIR, University of Pretoria South Africa	South African Department of Science and Technology, CSIR	Hayeshi *et al.*, 2013 [38]
PLGA Nanoparticles	PLGA, Curdlan	Drug delivery	University of Western Cape South Africa, CSIR, University of Pretoria South Africa, University of Johannesburg, South Africa, University of Witwatersrand South African	CSIR	Tukulula *et al.*, 2015 [39]
Eudragit RS PO-Tenofovir Nanoparticles es	Poly vinyl alcohol, sodium dodecyl Sulphate (SDS), Pluronic F127, Poloxamer 88, acetone, Tenofovir udragit RS PO, Distilled water	Improved HIV treatment	CSIR, Faculty of Agricultural, Science and Technology Northwest University		Matthola *et al.*, 2015 [40]
Microemulsion Tafenoquine (<20nm)	Tafenoquine, Sodium Oleate, Tween 80, Polyvinyl alcohol, Ethanol,	Improved malaria treatment	CSIR, University of Western Cape South Africa, University of Nairobi Kenya,	CSIR	Melariri P. *et al 2015* [41]

	Citronella essential oil		Kenya Medical Institute, Groove Schuster Hospital Cape Town, South Africa		
Polycaprolactone Nanoparticles, Liposomes	Polycaprolactone, Polyethylene glycol, IsoSuccinate, D-alpha Tocopherol, Tween 80,	Drug delivery in the treatment of Human African Trypanosomiasis	University of Western cape South Africa, Nelson Mandela African Institute of science and technology, Tanzania	Tanzanian Higher Education Student's Loan Board	Omarch *et al.*, *2009* [42]

Biomedical applications of nanomaterials have received considerable attention and interest from many foreign researchers over the past decade. However, despite these self-evident claims of its ability to solve social and health problems, development in nanotechnology is still nascent in Africa. However, some African researchers are zeroing in on advanced applications of nanotechnology in disease detection, diagnosis, drug delivery, monitoring and therapeutics.

East Africa

At the 2010 Common Market for Eastern and Southern Africa (COMESA) Summit, a new course was charted by the 19 member countries to harness, promote and utilize nanotechnology with special focus on its application in various key areas such as medical treatment. However, this goal has not been fully achieved.

The role of different nanotechnology-based drug delivery strategies to the brain has been studied. This includes the manufacture and use of liposomes, nanoparticles, vector peptides and amino acids starting with the appropriate surface modification targeted at the blood brain barrier and brain cerebrospinal fluid barriers. However, even after the application of this technology, successful delivery across the blood brain barrier has been achieved only for some therapeutic agents. This is due to narrow spectrum of the few developed nanoparticles for specific agents. Therefore, further researches should be done to widen up the range of the carrier particles.[6]

Silver Phyto-nanoparticles has been synthesized from silver nitrate solution using the extract of *Cleome viscosa* as reducing agent through a cost effective and environment friendly technique. In the process of synthesizing silver nanoparticle, there was a rapid reduction of silver ions to form of stable crystalline silver nanoparticles in the solution. The synthesis of silver Phyto-nanoparticles was prepared by adding silver nitrate solution [3 mM] to the plant extract. Nanoparticles were characterized using UV-Visible absorption spectroscopy, FTIR, X-Ray Diffraction, TEM AND SEM analysis.[2] The herbal leaves were used in isolating the silver Phyto-nanoparticles and tested for antimicrobial activity. The tests cultures include in this study were *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *E. coli*, *Vibrio cholerae*, and *Salmonella sp*. The maximum inhibitory effect using 3 mM silver nitrate against the microbes were obtained and served as the standard. They concluded that the extract of *Cleome viscose* is capable of producing silver nanoparticles which are stable in solution, using environmentally friendly natural resources as an alternative to chemical synthesis protocols at low cost. Also, it was confirmed that the capability of rendering antimicrobial efficacy is dependent on the composite release of silver at the core and proved to be active against the microbes.[6]

Schistosomiasis, also known as Bilharzia affects more than 250 million people. Commonly used diagnostic tools have very low validity and are not readily applied for rapid diagnosis in rural and remote areas. A simple and sensitive nano-biosensor which consisted of a nano-strip with immobilized gold nanoparticles conjugated with bilharzia antibody has been demonstrated to aid the diagnosis of bilharzia antigen in real samples using screen-printed electrodes. The nano biosensor was tested and validated using real stool samples. A detection limit of 8.3887×10^{-2} ng mL^{-1} and a detection range of 1.13×10^{-1} ng mL^{-1} to 2.3×10^{-3} ng mL^{-1} of bilharzia antigen in stool were observed. This nano-biosensor can be fabricated to nano-kits which can be distributed to bilharzia-endemic areas in Kenya where it can be used for point-of-care devices to detect bilharzia antigen in real samples thereby facilitating early diagnosis and treatment of bilharzia. [3]

Afzelia quanzensis bark extract has been utilized in the synthesis of silver nanoparticles (AgNPs). The characteristic absorption band when analyzed with UV-Vis spectrum was observed at 427 nm. Furthermore, the nanoparticles were spherical in shape and size ranged from 10 to 80 nm as observed through SEM analysis. In addition, the X-ray diffraction showed that the silver nanoparticles are crystalline in nature and have a face-centered cubic structure. Followed an FTIR analysis, the

presence of phytochemical functional groups such as carboxyl (-C=0) and amine (N-H) in *Afzelia quanzensis* bark extract further confirmed the reducing ability for nanoparticles formation. Interestingly, the synthesized silver nanoparticles at 50 mgL^{-1} concentration showed significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus.* This method represents an example of clean, nontoxic and eco-friendly method for obtaining silver nanoparticles and recommended further studies to isolate and quantify the different phytochemical components and to study their pharmacological properties after synthesizing the silver nanoparticles from the specific phytochemicals is required.[5]

A study demonstrated the extraction of Zinc oxide (ZnO) nanoparticles by green chemical reduction method from the bio-components of leaves extract of Gigantic Swallow Wort. FT-IR Spectroscopy and X-Ray Diffraction (XRD) characterizations were done for synthesized ZnO nanoparticles. The FT-IR studies showed an absorption peak at 473.33 cm^{-1} (Zn-O linkage) indicating the formation of zinc oxide nanoparticles. Using XRD analysis, the structure of the ZnO particles was reported as hexagonal with average particle size 28.38 nm. They concluded that the synthesis of ZnO NPs by the green chemical reduction method using Gigantic-Swallow-Wort leaf extract is simple and cost effective which can be harnessed in drug delivery.[7]

North Africa

North Africa researchers have developed spherical gold nanoparticles prototype of about 14 nm for direct and inexpensive detection of tuberculosis. The prototype is simple, sensitive, rapid and can be substitute PCR-based detection. This developed assay may show potential in the clinical diagnosis of TB especially in developing countries. [9]

Several Egyptian researchers have also developed inhalable nanocarriers for localized delivery of bioactive agents to lung tissues. Two formulation approaches were utilized including nebulizable nanosuspension and dry powder nanocomposites, use of poly (D, L-Lactide-co-glycolic acid) nanoparticles for combined pulmonary delivery of celecoxib and herbal flavonoid naringin to lung cancer cells. (Upon their nebulization, the nanoparticles displayed good aerosolization behavior demonstrated as small droplet size of 3.75mm and fine particle fraction (FPF) of 71% ensuring deep lung deposition).[11]

Due to their ability to bind to bacterial DNA and create holes in cell walls leading to cell death, gold nanoparticles have been used a good antibacterial agent Gold nanoparticle (28.9 – 37.65 nm) were embedded in poloxamer/hydroxypropyl methyl cellulose (HPMC) thermo-responsive gels for wound healing purposes to avoid the adverse effects of antibiotic systemic therapy. As revealed by burn-induced infected wounds in mice, the formulation demonstrated powerful antibacterial properties against the gram-positive bacteria *Staphylococcus aureus*, resulting in complete wound healing compared to mice treated with silver sulphadiazine.[11]

Carbon nanotubes are used in cancer treatment as anticancer drug carrier and targeted at cancer cells when nanotubes are attached with folic acid. ZnO NPs are used as an anticancer agent directly on cancer cells through three mechanisms; causing zinc-mediated protein activity disequilibrium, increasing intracellular oxidative stress and DNA damage. Copper NPs are used as DNA-cleavage and potent anticancer agents due to their binding capacity and modifiable surface properties can also act as effective drug delivery system and can be used in bioimaging in the form of transferrin (Tf) template copper nanoclusters (Tf-CuNCs) which enhanced luminescence and imaging.[12]

West Africa

Nanoparticles synthesis and its biomedical application are gaining wide audience in Nigeria, although when compared with other developing African countries like South Africa and Egypt, it is still at a low point. The challenges and prospects of venturing into Nanotechnology research has been attributed to educational, infrastructural and funding factors. More funds must be injected into the educational system and a change in curriculum to accommodate nanotechnology from the undergraduate level must be implemented as well as the provision of government policies to favor nanotechnology advancement.[45]

The impacts of nanotechnology in the natural world, its methods of production, application and benefits as well as risks has been explored by African researchers. These researchers emphasized the concepts of nanotechnology as being geared towards overcoming the challenges of traditional drug delivery system. This involves the development and manufacturing of nanostructures utilized in drug delivery, their techniques of fabrication and the challenges which is related to its impact on drug effectiveness, stability, pharmacokinetics, toxicity and drug regulation. They concluded that scientists in the field of biomedical sciences and other fields should be abreast with and employ nanotechnology for the advancement of research and development.[46,47]

In order to demonstrate 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 reviewed which included the discussion of the properties of the nanoparticles. These biomedical applications are to combat the numerous problems facing mankind; predominantly the antimicrobial resistance phenomena, control of vector-borne diseases, mitigation of the deleterious of free

radical species among others. In conclusion, this review underscored the importance of these nanoparticles in the emerging disciplines of nano-and biomedicine.[24]

Diseases are a major drawback in livestock production, its consequences as well as other gaps in the application of nanotechnology in Veterinary studies has been examined. The application of nanotechnology in the treatment of African animal Trypanosomiasis involves the use of porous cationic nanoparticles to improve targeting of trypanosomes. Veterinary technology holds a great key in diagnostics and therapeutics of animal diseases and research needs to be intensified to breach the gaps. Molecular diagnostics and therapeutics can be combined with nanotechnology to boost the efficiency in the diagnosis and treatment of animal diseases for improved protein supply, food security as well as treatment of zoonotic diseases found in humans. Further investigations including the pre-treatment of mice with Protein Cage Nanoparticles (PCN) has been found to confer protection on mice against Influenza viruses, mouse pneumo-virus and mouse-adapted SARS-coronavirus.[48]

The application of nanotechnology in dentistry has given rise to the latest sub-field of Nano dentistry. A study reviewed several advances of nanotechnology in dentistry which 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 the selection of appropriate targets, component materials, and formulation strategies are critical to achieving successful outcomes in such endeavors.[59]

The toxicological effects of Nanoparticles by synthesizing ZnONPs using the leaf extract of *Solanum torvum* have also been investigated. 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. In conclusion, it was observed that there was a significant increase in the plasma zinc level in a dose and time dependent manner showing that biochemical markers for both renal and hepatic functions were affected by dermatological exposure to ZnO nanoparticle-hydrogel.[50]

Southern Africa

In Africa, South Africa is at the fore front of nanotechnology research and development with committed efforts by the government in establishing nanoscience centers, acquiring state of the art equipment and human capital development.

Studies on nanomaterials has led to the preparation of Polycaprolactone-Efavirenz nanoparticles by double emulsion spray-drying method and the effects of formulation parameters on the average particle size and polydispersity index (PDI) using the Taniguchi method were also investigated. The significance of the study is based on the fact that particle size plays a key role in determining the pharmacodynamics behavior such as degradation, uptake, clearance and toxicity during drug delivery. Results showed that the use of ethyl acetate as a solvent in the formulation yielded nanoparticles with particle sizes of less than 250+/-0.95 nm while for dichloromethane, the particle sizes were more than 360+/-19.96 nm. Following this, they concluded that the organic solvent used in the formulation of spray dried Efavirenz nanoparticles affects the particle size and PDI.[36]

Nanoencapsulation of drugs protects it from G.I.T degradation and consequent loss of efficacy. The degradation of the polymer can control the release of the drug which will ultimately reduce its frequency of administration [37]. Two different solvents (ethyl acetate and dichloromethane) and excipients (lactose and trehalose) were employed in nano encapsulating Lamivudine into biodegradable and biocompatible Poly epsilon Caprolactone (PCL) nanoparticles using the double emulsion spray drying method. The results obtained showed that ethyl acetate and lactose as solvents and excipients respectively, yielded products with small mean particle sizes and a good PDI compared to that obtained with dichloromethane and trehalose confirming that ethyl acetate and lactose are good solvent and excipient respectively in formulation of spray-dried PCL-LAM nanoparticles. Drug release studies carried out at different pH range mimicking the pH profile of the GIT showed that the rate of drug release increased as the pH increased. Since low pH values are similar to the conditions of the GIT, the formulation therefore has the potential of controlling the release of Lamivudine which will reduce its administration frequency in HIV treatment and consequently lead to a reduction in the side effects of the drug and improve patient compliance.[37]

At the council for scientific and industrial research (CSIR), the three first-line anti-TB drugs were encapsulated into biodegradable poly (D, L-lactic acid-co-glycolic acid) PLGA nanoparticles using an emulsion spray-drying technique with encapsulation efficiencies of 82% for rifampicin, 75% for pyrazinamide and 62% for isoniazid. *In vitro* studies demonstrated that the efficacy of the encapsulated anti-TB drugs was not affected by the spray-drying technique while *in vivo* studies in mice showed a sustained drug release profile of encapsulated anti-TB drugs with concentrations above the MIC level for 5days compared to non-encapsulated drugs with concentrations below the MIC level within a 16h period. It was then concluded that the formulation of anti-TB drugs into nanoparticles could potentially control the

release of the drug thereby improving TB drug delivery by reducing the frequency of administration and ultimately improving compliance and will also reduce the side effects of treatment. These results are consistent with reports that Nanoencapsulation provides protection from the harsh conditions of the GIT especially for acid-labile drugs such as rifampicin.[38]

Also at the CSIR an investigation into the immunostimulatory activity of Curdlan-Conjugated PLGA nanoparticles was carried out. An emulsion solvent evaporation technique was used to synthesize the nanoparticles after which Curdlan was conjugated to PLGA and the resultant polymer duly characterized. Immunostimulatory activity of the polymer nanoparticles was observed and the results demonstrated that stimulation of macrophages was achieved by C-PLGA nanoparticles through enhanced production of phosphorylated ERK. Nanoparticle uptake by the macrophages was reported to be calcium dependent. Drug release studies using rifampicin as the loaded drug showed a slow release of the drug by the nanoparticles. This concludes that PLGA nanoparticles can stimulate macrophages as well as sustain drug release which means a double therapeutic role for its application in the treatment of infectious diseases such as tuberculosis.[39]

In 2015 an optimized nanotechnology-based delivery system for the anti-retroviral drug tenofovir was developed. The optimization was targeted at obtaining nanoparticles with good particle size and PDI, high zeta potential and high EE. The effect of independent variables on each factor was studied and it was concluded that 50 mg of polymer, 3% concentration of surfactant (SDS) and 45 minutes of sonication time is required for optimal formulation of Eudragit RS PO-Tenofovir nanocarriers. The release profile of the drug from the polymer matrix showed sustained release of tenofovir indicated by a slow rate of absorption in acidic media (pH 1.5) compared to a higher release rate in alkaline media (pH 7.4). In conclusion, tenofovir was successfully encapsulated in Eudragit RS PO nanoparticles using the BBD resulting in products with good physicochemical characteristics that are able to prolong the release of the drug. This will ultimately reduce its frequency of administration, increase bioavailability and efficacy in HIV treatment with reduced side effects.[40]

The biomedical application of nanotechnology in malaria treatment was explored when the anti-malaria efficacy of nano-formulated Tafenoquine (nano-TQ) was evaluated. Tafenoquine (TQ) is a new synthetic analogue of primaquine but more effective and has a longer half-life. It has poor aqueous solubility and is associated with hemolysis in glucose-6-phosphate deficient (D6PD) individuals. They hypothesized that improving the solubility of tafenoquine in a microemulsion (nano-TQ) will reduce its toxic effects especially in G6PD individuals and hence improve its therapeutic efficacy. In vitro studies were carried out to evaluate the anti-plasmodia activity of nano-TQ and non-formulated tafenoquine (TQ) and it was reported that the concentration inhibiting 50% of parasite growth (IC50) was not significantly different for nano-TQ and TQ suggesting that the efficacy of TQ was not affected by the formulation technique used. In vivo studies carried out on mice demonstrated that micro emulsion formulation of TQ resulted in an increase in its solubility thereby enhancing its absorption and consequently improving its bioavailability. Other pharmacokinetic behaviors such as the elimination half-life, the peak plasma concentration (Cmax) and the time taken for maximum plasma concentration (Tmax) were significantly improved compared to non-formulated tafenoquine (TQ).

Results also showed that the G6PD toxicity of nano TQ reduced greatly compared to non-formulated TQ and primaquine (PQ). It was recorded that at 10mg/kg dose, 62% percentage loss of human red blood cells (HuRBC) was observed with nano-TQ while a 5mg/kg dose of non-formulated TQ gave a comparable result of 59% suggesting that the dose of nano-TQ can be increased without any significant increase in toxicity as was observed in G6PD deficient mice. They concluded that nano-formulation of tafenoquine can improve its solubility and will consequently enhance its bioavailability and reduce toxicity as was observed in mouse models.[41]

At the University of Western Cape, research in nanotechnology also focuses on the application of nanomedicine in the treatment of tuberculosis. One of such applications involves the use of nanoparticles to target macrophages where the bacteria that causes tuberculosis (Mycobacterium tuberculosis) resides. They are used to increase the absorption of drugs thereby increasing the bioavailability of anti-TB drugs. Due to their unique particle size, they undergo high uptake into cells where they are able to deliver large amounts of drug at infection site.[43]

They are also engineered to deliver signals that activate the immune system cells to act against the bacteria and kill them. This is because inside the macrophages, the *M. tuberculosis* multiply and are able to escape detection by the body's immune system but activation of the immune system (immunotherapy) in combination with chemotherapeutic agents will provide a double defense therapy against the disease. This can help prevent the generation of drug-resistant TB strains.[43]

The incorporation of drugs into nanocarriers is also known to enhance its transportation across the blood brain barrier (BBB). To explore the possibility of reducing the toxicity of pentamidine using liposomes and PCL nanoparticles as delivery systems across the BBB, a double solvent evaporation method was used to synthesize pentamidine-PCL loaded nanoparticles while

thin lipid film hydration technique was used to prepare pentamidine loaded liposomes. Pentamidine is a drug used in the treatment of Human African Trypanosomiasis (HAT). It is poorly absorbed by the body with very poor bioavailability. It is also associated with undesirable side effects such as cardiac arrhythmia and liver and kidney problems. The synthesized nanoparticles were found to be in the nano range with the average mean size of loaded PCL nanoparticles and liposomes of smaller nano size than the unloaded nanocarriers and they possessed good physicochemical properties with a loading capacity of 0.1ug/mg and 0.178ug/mg for PCL nanoparticles and liposomes respectively. Drug release studies showed that as polymer degradation occurred with PCL nanoparticles, slow and sustained release of the drug also took place. It was also recorded that pentamidine loaded liposomes penetrated the barrier more as indicated by lower trans-endothelial electrical resistance (TEER) values compared to pentamidine loaded PCL and free pentamidine. This was stated to be largely due to its lipophilic nature although high concentrations of liposomes and PCL nanoparticles were found to be cytotoxic. In conclusion, liposomes transported a higher amount of drug across the barrier than the PCL nanoparticles and hence a better delivery vehicle for pentamidine across the BBB.[42]

One of such biomedical application of nanomaterials was aimed at reducing the hemolytic effect of mefloquine by incorporating it onto a lipid based nano drug delivery system known as pheroid vesicles for use in malaria treatment. In vitro studies revealed that its hemolytic effect was reduced by about 75% and also a 60% reduction in its cytotoxicity against Human neuroblastoma cells was recorded. In vivo studies were carried out using mice models and this revealed that the pharmacokinetic behaviors of mefloquine were not altered by the incorporation. They concluded that the therapeutic outcome of malaria treatment and prophylaxis with mefloquine can be improved by incorporation into pheroid vesicles.[44]

RECOMENDATIONS

1. Improved government funding and spending on research and development which will inspire both public and private participation.
2. Creation of national policy and enactment of proper regulatory framework with the aim to promote nanotechnology engagement and activities.
3. Establishment of well-equipped nanotechnology centers and institutes with state-of-the-art facilities in combination with proper and organized trainings for personnel to ensure competence and efficiency.
4. Curriculum development to include educational programs that provides trainings in nanotechnology at all levels of tertiary education.
5. Multilateral and bilateral collaboration with countries that have strong nanotechnology capabilities and accomplishments in order to improve human capital development and also for access to funding and equipment.
6. Private-public partnerships between industries, institutions and independent researchers through provision of research grants and other required support with an aim to translate fundamental research into end products.
7. Access to information which will include workshops, trainings and conferences, short courses in order to encourage and strengthen individual participation.

CONCLUSION

The advancement of biomedical research through the use of nanomaterials is very critical for the growth and development of Africa. Advancements in nanotechnology are already making impact in medical care. With the development of drugs such as Abraxane® and Doxil® which are currently being used in the treatment of cancer and many more still under investigation, one cannot refute the fact that it holds promises of revolutionizing industrial processes and the manner in which healthcare is delivered.

Developed and some developing countries have long recognized the technological and economic potentials of nanotechnology and have taken considerable measures to invest in its advancement which has brought about a consistent progress in its application in end products. However, Africa in general has not participated effectively in this expanding global trend. Most African nations despite having interests are yet to establish a systematic approach for its exploration, exploitation, implementation and application in new products.

Nanotechnology presents an opportunity for developing countries especially in Africa to improve industrial processes and capabilities while tapering their economic and technological reliance on developed countries. It promises to provide a more advanced and cost-effective solutions to the challenges (related to disease diagnosis, treatment and management) facing the developing and least developed countries which will ultimately result in better healthcare delivery for Africa and the world at large.

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CONFLICT OF INTEREST

None

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