Research, Society and Development, v. 10, n. 16, e399101623406, 2021
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v10i16.23406

Recent advances (2016 - 2020) in green synthesis of metal oxide nanoparticles: An overview

Avanços recentes (2016 - 2020) na síntese verde de nanopartículas de óxidos metálicos: Uma visão geral

Avances recientes (2016 - 2020) en la síntesis verde de nanopartículas de óxidos metálicos: Una descripción general

Received: 11/17/2021 | Reviewed: 11/27/2021 | Accept: 12/06/2021| Published: 12/15/2021

Marta Bianca da Costa Rocha
ORCID: https://orcid.org/0000-0002-7032-8963
Federal Institute of Education, Science and Technology of Maranhão, Brazil
E-mail: marta.biancacr@gmail.com
Tomaz Rodrigues de Araújo
ORCID: https://orcid.org/0000-0002-5368-9775
Federal University of Rio Grande do Norte, Brazil
E-mail: tomaz.rdaraujo@bct.ect.ufrn.br
Rodolfo Luiz Bezerra de Araújo Medeiros
ORCID: https://orcid.org/0000-0002-3072-1250
Federal Institute of Education, Science and Technology of Maranhão, Brazil
E-mail: rodolfoluiz.eng@gmail.com
Marcelo Moizinho Oliveira
ORCID: https://orcid.org/0000-0003-4991-8157
Federal Institute of Education, Science and Technology of Maranhão, Brazil
E-mail: marcelo@ifma.edu.br
Gilvan Pereira de Figueredo
ORCID: https://orcid.org/0000-0002-3989-1360
Federal Institute of Education, Science and Technology of Maranhão, Brazil
E-mail: gilvanfigueredo@ifma.edu.br

Abstract

The development of products and processes which are more ecological has been a source of interest in research in recent decades. Thus, researchers have developed several methods to improve the synthesis of oxides and metals in a more ecological way. Green synthesis has become a method that is being widely used for presenting low temperature, low cost and great availability of raw material. Some biological sources such as fungi, bacteria and plants are used in this route, but plant extracts are the most used in the literature. Various parts of the plant such as the roots, bark, flowers, fruits, stem, seeds, and leaves are rich in secondary metabolites such as: flavonoids, phenols, steroids, terpenoids, alkaloids, saponins and phenolic compounds, which play an essential role in the complexation, polymerization, capping and stabilization processes that generate oxides. The methodology used in the synthesis process significantly interferes in some properties and characteristics of the same oxide as its morphology. In this sense, this paper presents a review on green synthesis in obtaining oxides and their morphologies.

Keywords: Green chemistry; Ceramics; Synthesis route; Nanomaterials.

Resumo

O desenvolvimento de produtos e processos que sejam mais ecológicos têm sido motivo de interesse de pesquisas nas últimas décadas. Dessa forma, os pesquisadores têm desenvolvido diversos métodos para aprimorar a síntese de óxidos e metais de forma mais ecológica. A síntese verde tem se tornado um método que está sendo bastante utilizado por apresentar baixa toxidade, baixo custo e grande disponibilidade de matéria prima. Nesta rota são utilizadas algumas fontes biológicas como fungos, bactérias e plantas, porém os extratos de plantas são os mais relatados na literatura. Várias partes da planta como raízes, casca, flores, frutos, caule, sementes e folhas são ricas em metabólitos secundários como: flavonoides, fenóis, esteroides, terpenóides, alcaloides, saponinas e compostos fenólicos, que desempenham um papel essencial nos processos de complexação, polimerização, capeamento e estabilização na síntese verde de óxidos. A metodologia utilizada no processo de síntese interfere de maneira significativa nas propriedades e características dos óxidos, especialmente em sua morfologia. Neste sentido, este trabalho apresenta uma análise dos avanços registrados entre 2016 e 2020 no campo da síntese verde na obtenção de óxidos e suas diferentes morfologias.

Palavras-chave: Química verde; Cerâmicos; Rota de síntese; Nanomateriais.

Resumen
El desarrollo de productos y procesos más ecológicos ha atraído mucha atención en los últimos años. Así, los investigadores han desarrollado varios métodos para mejorar la síntesis de óxidos y metales de una forma más ecológica. La síntesis verde se ha convertido en un método muy utilizado por su baja toxicidad, bajo costo y alta disponibilidad de materia prima. En esta ruta se utilizan algunas fuentes biológicas como hongos, bacterias y plantas, pero los extractos de plantas son los más utilizados en la literatura. Varias partes de la planta como raíces, corteza, flores, frutos, tallo, semillas y hojas son ricas en metabolitos secundarios como: flavonoides, fenoles, esteroides, terpenoides, alcaloides, saponinas y compuestos fenólicos juegan un papel esencial en el proceso de polimerización, cableado y estabilización que generan los óxidos. La metodología utilizada en el proceso de síntesis interfiere aproximadamente en algunas propiedades y características del mismo óxido como su morfología. En este sentido, este trabajo presenta una revisión de la síntesis verde en la obtención de óxidos y sus morfologías.
Palabras clave: Química verde; Cerámica; Ruta de sínteses; Nanomateriales.

1. Introduction

Science and technology at the nanometric scale have attracted a lot of attention from researchers due to its use and its varied applications. Many advanced devices rely on nanostructured materials. Thus, nanotechnology has emerged as a new research field regarding the preparation of nanomaterials and nanoparticles (NPs) because of its multifunctional properties and efficiency. Nanometric materials with unique optical, magnetic, electronic and catalytic properties, as well as distinct structure, composition and morphology characteristics have drawn attention to different areas such as chemistry, physics, materials science, and engineering, etc.

Nanoparticles are generally obtained by two methods: “top-down” and “bottom-up”. The first approach is based on fragmenting larger structures (bulk) using ablation, grinding and cutting techniques until reaching a nanometric structure. However, the bottom-up approach usually disposes of the chemical properties of atoms and molecules to attract each other and agglomerate to form an organized structure of nanometric size. Some synthesis routes that use this approach include: sol-gel method, chemical vapor deposition, Pechini, microemulsion, and green synthesis, etc. (Aarthye *et al*., 2021).

Due to environmental concerns, the development of products and processes which are more ecological has gained a lot of attention in recent years. In this sense, researchers have developed several methods to improve the synthesis of metals and oxides using more ecological routes. The biosynthesis or green synthesis method presents itself as an alternative route to avoid the use of chemicals, reactions and processes that are dangerous to human beings and/or the environment, in addition to presenting a low production cost and being able to obtain a product with a high yield. In this synthesis, nanomaterials are obtained from extracts of plants, microorganisms, fungi, yeasts, algae, and so on (Aarthye *et al*., 2021; Abinaya *et al*., 2021), which generally makes it a low-cost process, in addition to wide availability and using less toxic reagents. Fatty acids, polysaccharides, proteins, phenolic compounds, secondary metabolites present in plants and microorganisms help in the synthesis process of oxides and metals. Plant extracts are the most found in the literature among the alternative media used due to their rapid synthesis and wide availability (Moraes *et al*., 2021). Another potential point in green synthesis is the possibility of infinite combinations of extracts to manipulate the structure and morphology of nanoparticles.

Aiming to explore the potential of green synthesis, the objective of this work is to present recent studies (2016 – 2020) on this method in producing metal oxides, with an emphasis on the effects of the synthesis process on the morphology of the obtained nanoparticles.

2. Methodology

This work consisted of a review integrated to the literature, conducted in the second half of 2021. According to Fink (2019), the use of this type of research is an organized and reproducible way which provides quick access to results on a given subject, such as also carrying out a mapping of what the literature presents about some given content, helping to delimit research and to show how studies differ and progress in relation to the knowledge already carried out in the area (Lüdke *et al.*, 2012).

This literature review was carried out by searching the SCOPUS, Scielo, Google Scholar, CAPES Periodicals, and Science Direct digital databases, covering the period from 2016 to 2021 and using the following descriptors: green synthesis, oxides, fungi, plants, and microorganisms. Exclusion criteria were: articles published more than 6 years ago, articles in abstract format, monographs, Master's dissertations, abstracts of works and doctoral theses.

3. Results and Discussion

3.1 Plant extract use

There are several biological sources used in this type of synthesis, however the use of plant extracts are the most reported in the literature, as plants are true "biological factories" of nature and present huge metabolic composition that will help in the formation of nanoparticles, in addition to being a faster synthesis compared to that using micro-organisms (Aarthye *et al.*, 2021; Bibi *et al.*, 2019; Iravani, 2011).

Various parts of the plant are used for synthesis such as roots, flowers, seeds and stems. But leaves are the most widely reported in the literature. Plant extracts have several components that can act as reducing, complexing, polymerizing and stabilizing agents due to the combination of molecules present in the extract, and thus help in the synthesis (Shamaila *et al.*, 2016). Among these, the following stand out: amino acids, flavonoids, phenols, citric acid, terpenoids, bioactive polyphenols, and alkaloids, among other organic compounds such as alcohols, aldehydes and amines (Iravani, 2011; Shamaila *et al.*, 2016). Polyphenol phytomolecules have antioxidant capacity which are easily absorbed by nanoparticles that help to reduce the nanoparticle size, for example (Aarthye *et al.*, 2021). Table 1 shows the main works found in the literature (2016 – 2020) on oxides synthesized using plant extracts and Figure 1 makes the correlations between the characteristics.

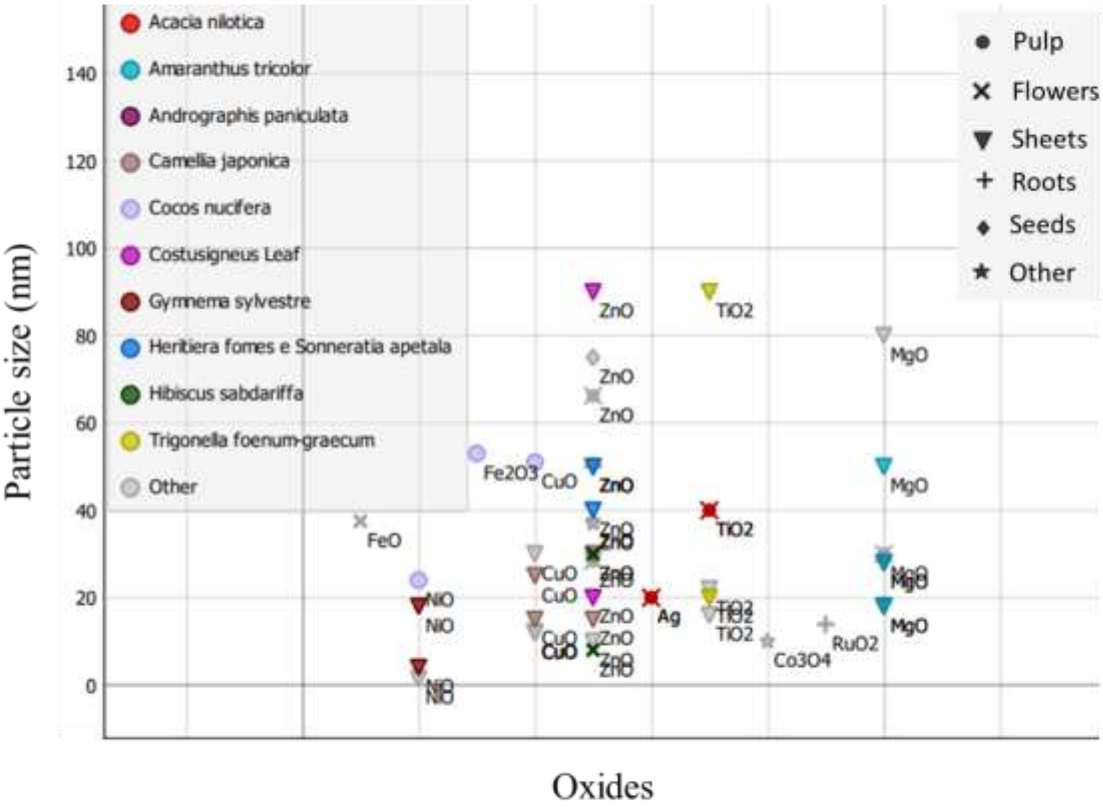
Table 1. Oxides synthesized by the green synthesis method using plant extracts.

Plant	Part of the plant used in the synthesis	Oxide obtained	Particle size (nm)	Morphology	Reference
Punica granatum	seeds	Fe_2O_3	-	Spherical	(Bibi *et al.*, 2019)
Avicennia marina	flowers	FeO	37.5	Spherical	(Karpagavinayagam *et al.*, 2019)
Gymnema sylvestre	leaves	NiO	4-18	Spherical	(Ramalingam *et al.*, 2019)
Ananas comosus	leaves	NiO	1.41 – 1.76	Monodispersible	(Olajire *et al.*, 2020)
Cocos nucifera	Pulp	CuO;	51	Spherical	(Muthuvinothini *et al.*, 2019)
Cocos nucifera	Pulp	NiO;	24	Cubic monodispersed	
Cocos nucifera	Pulp	Fe_2O_3	53	Distorted spherical	
Heritiera fomes and Sonneratia apetala	leaves	ZnO	400-500	-	(Thatoi *et al.*, 2016)
Linnum usitatissimum	seeds	ZnO	75	Nano leaves	(Moghaddas *et al.*, 2019)
Costusigneus Leaf	leaves	ZnO	20-90	Spherical	(Chinnasamy *et al.*, 2018)
Musa spp.	bark	ZnO	370	Sphere/globular	(Dutta *et al.*, 2019)
Stevia (adoçante natural)	leaves	ZnO	10-50	Retangular	(Khatami *et al.*, 2018)
Trianthema portulacastrum	-	ZnO	28.4-66.2	Aggregated	(Khan *et al.*, 2019)
Averrhoa bilimbi (L)	fruit	ZnO	37.5	Spherical	(Ramanarayanan *et al.*, 2018)

Typha latifolia.L	leaves	ZnO	-	Nano flowers	(Kumar *et al.*, 2019)
Hibiscus sabdariffa	flower	ZnO	8- 30	Semi-spherical	(Soto-Robles *et al.*, 2019)
Codonopsis lanceolata	roots	ZnO	500	Flower	(Lu *et al.*, 2019)
Scutellaria baicalensis	roots	ZnO	50	Spherical	(Chen *et al.*, 2019)
Calliandra haematocephala	leaves	ZnO	-	Flower shape	(Vinayagam *et al.*, 2020)
Camellia japonica	leaves	ZnO	15-30	Spherical	(Maruthupandy *et al.*, 2017)
Acacia nilotica	-	Ag / TiO_2	20-40	Spherical	(Rao *et al.*, 2019)
Esbania grandiflora	leaves	TiO_2	160-220	Spherical	(Srinivasan *et al.*, 2019)
Trigonella foenum-graecum	leaves	TiO_2	20-90	Spherical	(Subhapriya *et al.*, 2018)
Calotropis procera	latex	Co_3O_4	10	Spherical	(Dubey *et al.*, 2018)
Anacyclus pyrethrum	root	RuO_2	13.9	Almost spherical	(Nisha *et al.*, 2020)
Azadirachta indica	leaves	CuO	12	Spherical	(Rehana *et al.*, 2017)
Hibiscus rosa-sinensis	leaves	CuO	12	Esférica	
Murraya koenigii	leaves	CuO	12	Spherical	
Moringa oleifera	leaves	CuO	12	Spherical	
Tamarindus indica	leaves	CuO	12	Spherical	
Camellia japonica	leaves	CuO	15-25	Spherical	(Maruthupandy *et al.*, 2017)
Thymus vulgaris L.	leaves	CuO	30	Spherical	(Nasrollahzadeh *et al.*, 2016)
Acanthospermum hispidum	leaves	CuO	-	Spherical	(Gowri *et al.*, 2019)
Amaranthus tricolor	leaves	MgO	18-28	Hexagonal	(Jeevanandam *et al.*, 2017)
Amaranthus blitum	leaves	MgO	50-80	Spherical	
Andrographis paniculata	leaves	MgO	18-28	Spherical	
Solanum trilobatum	-	MgO	30	Spherical	

Source: Authors.

Figure 1. Relationship between particle size and plant part and species.



Source: Authors.

These extracts also behave as a capping agent which controls the particle shape and size in the synthesized material. A very important fact in this type of route is that each plant component presents a variation in its composition or phytochemical concentration according to the tissue or the conditions it may be in, such as temperature and humidity, for example (Narendhran *et al*., 2019). Thus, both the phytochemical composition and the selected plant part will influence the efficiency of the extract in forming the desired nanoparticles (Shamaila *et al*., 2016). One of the criteria for selecting the plant is its geographical disposition, an unprecedented report, in addition to its phytochemical composition (Das *et al*., 2013).

The morphological properties are influenced by several aspects such as the pH, synthesis temperature, the extract concentration and volume. The review work by Akintelu *et al*. (2020) showed how the type of extract used in the synthesis, as well as its concentration, influenced the synthesis of copper oxide, obtaining different molds and applications. Devatha *et al*. (2018) identified and quantized the polyphenols present in the extracts using HPLC (High Performance Liquid Chromatography) and concluded that the greater the availability of these phytochemicals present in the medium, the faster their nanoparticle formation rate. Another important feature in obtaining nanoparticles is the volume and extract ratio used and the type of extract and its concentration, which was observed by Devatha *et al*. (2018) and Fazlzadeh *et al*. (2017). The authors observed that these parameters significantly influence both morphological and biological properties of nanoparticles. Devatha *et al*. (2018) found that the 1:2 ratio of iron particles had sizes 98–200 nm, while the others had particles ranging between 200 and 600 nm and these had more agglomerates. Its bacterial inhibition activity increased as the proportions increased from 1:2 to 1:5. A study by Fazlzadeh *et al*. (2017) verified that the different plant extracts interfered in the shapes, sizes and characteristics of the nanoparticles and thus altered the ability to remove aqueous pollutants.

According to Table 1, it is possible to observe that the main oxides studied are NiO, ZnO and MgO, as they are more interesting for biological, photocatalytic, catalytic, and biosensor activities (among others). It is also possible to notice that there is a variation in morphology for ZnO from a spherical to flower type when using *Scutellaria baicalensis* and *Camellia japonica*, as well as *Codonopsis lanceolata* and *Calliandra haematocephala* plants, which is due to the fact that they present differences in the chemical composition of the extract and under synthesis conditions. However, there is no difference in morphology for CuO, only differences in crystallite size. Figure 1 shows the relationship of oxides with particle sizes smaller than 20 nm using extracts obtained from leaves, regardless of the species used to extract the phytochemicals. However, this can be directly attributed to the use of the leaf to obtain nanoparticles, since the large volume of work in the literature is using leaves combined with other process variables such as pH, calcination temperature or the extract concentration.

3.2 Bacteria use

The synthesis of metals and oxides can occur via an extra or intracellular mechanism when green synthesis occurs through using bacteria. In the first case (extracellular), studies suggest that the growth and stabilization of nanoparticles are made from enzymes and proteins secreted by bacteria (Bandeira *et al*., 2020). Synthesis in the intracellular method begins with electrostatic interaction of the cell wall (negative charge) with metal ions (positive charge). Then these ions are captured into the cell interior after contact, and the enzymes present in the cell wall will reduce the ions to nanoparticles (Hulkoti *et al*., 2014).

From the medium, intra- and extracellular routes obtained different morphologies of oxides with varied sizes. The use of bacterial cultures has advantages such as: low cost-benefit, easy culture, moderate experimental conditions and stability in the production of nanoparticles (Ghasemi *et al*., 2017). Several bacteria were used as a biological source of green synthesis to obtain oxides. Table 2 presents some works which performed this biosynthesis.

Table 2. Synthesis of metal oxides using bacteria.

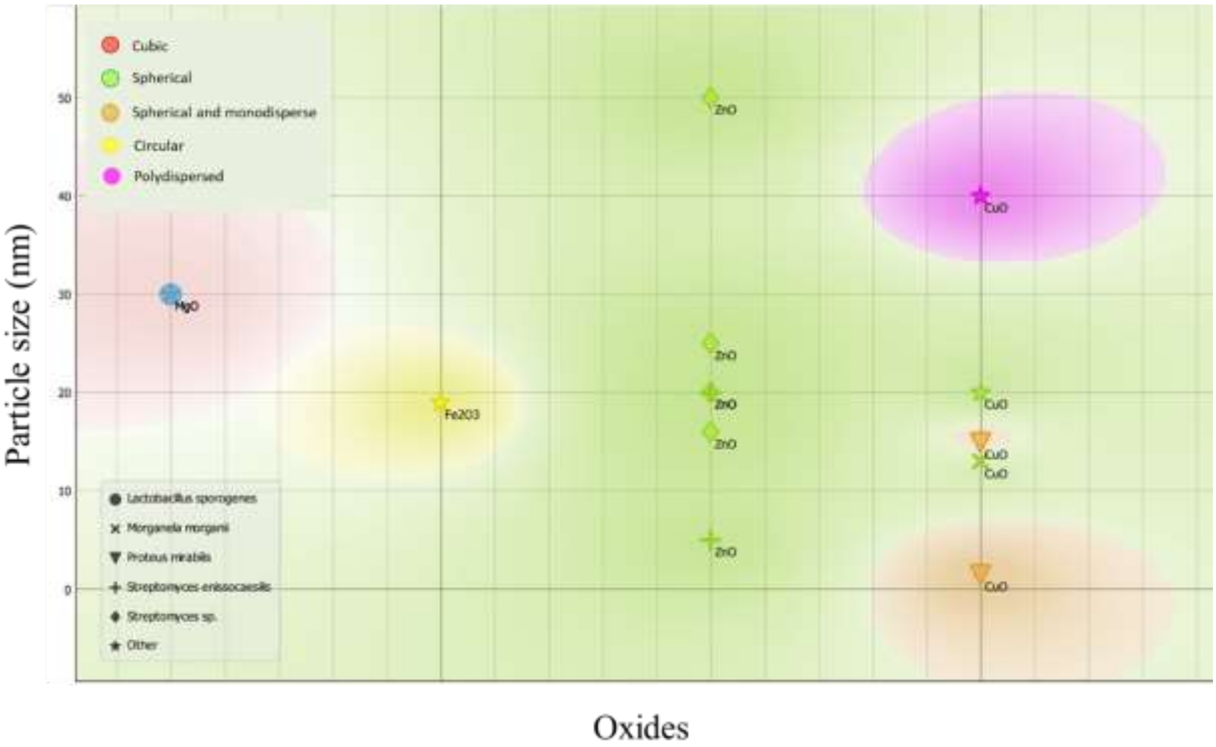
Bacteria	Oxide obtained	Particle size (nm)	Morphology	Reference
Lactobacillus plantarum	MgO	30	Cubic	(Mohanasrinivasan *et al*., 2018)
Lactobacillus sporogenes	MgO	30	-	
Desulfovibrio, cepa LS4	Fe_2O_3	19	Rounded	(Das *et al*., 2018)
Streptomyces sp.	ZnO	16-25	Spherical	(Shanmugasundaram *et al*., 2017)
Streptomyces sp.	ZnO	20-50	Spherical	(Balraj *et al*., 2017)
Streptomyces enissocaesilis	ZnO	5-20	Spherical	(Shaaban *et al*., 2018)
Desulfovibrio marinisediminis	CuO	400	Polydispersed	(Alasvand *et al*., 2016)
Morganela morganii	CuO	13	Spherical	(Ghasemi *et al*., 2017)
Proteus mirabilis	CuO	1.44-14.9	Spherical and monodispersed	(Eltarahony *et al*., 2018)
Lactobacillus casei	CuO	200	Spherical	(Kouhkan *et al*., 2020)

Source: Authors.

In the work by Jacob *et al*. (2019), it was found that the particle texture and size are affected with the variation in the pH of the medium in the synthesis of iron oxide with *Streptomyces* spp. via the extracellular pathway. The pH considered ideal for this synthesis was 7 and 9 nm, and they also concluded that temperature is an important factor in the morphology of the material.

According to Table 2, it is possible to observe that the main oxides studied are MgO, ZnO and CuO due to their application in several areas such as: catalysis, semiconductor, biomaterial, environmental and so on. It is also possible to notice that there was no variation in morphology for ZnO and CuO, but only differences in crystallite size. Figure 2 indicates that the spherical morphology is related to nanoparticles smaller than 10 nm.

Figure 2. Relationship between particle size and bacterial species and morphology.



Source: Authors.

3.3 Fungi use

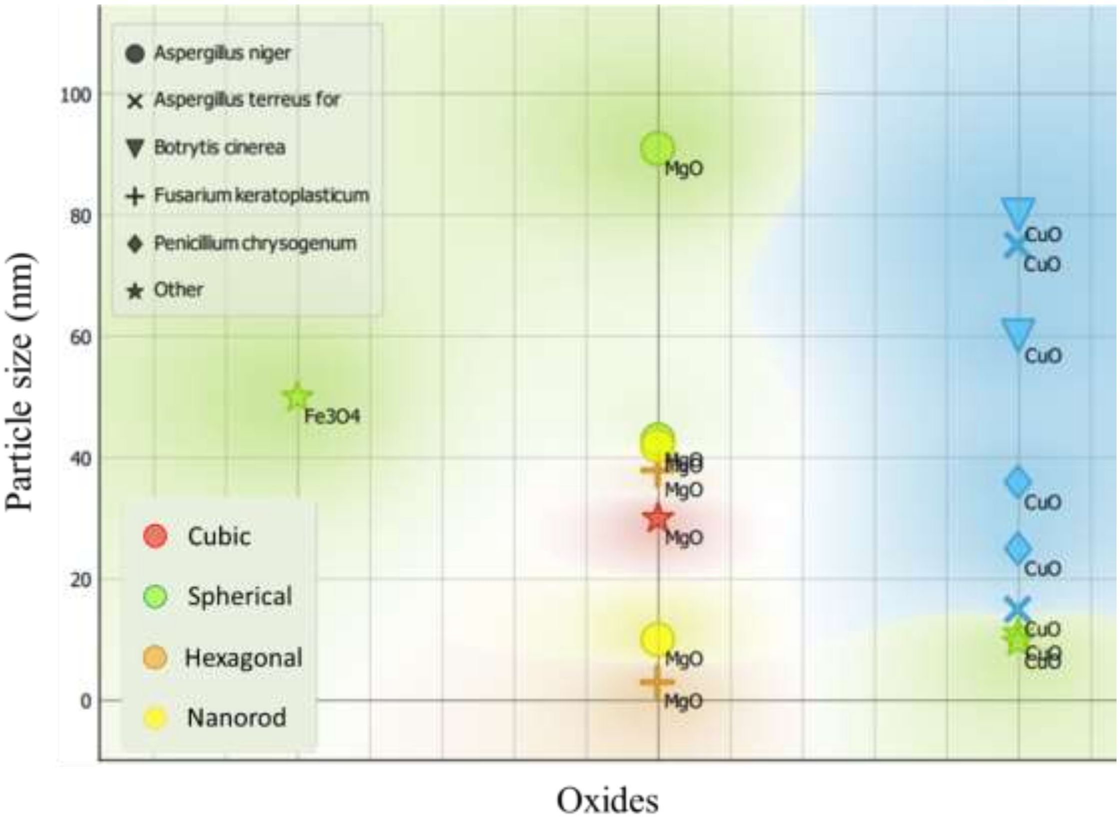
Fungi can be very promising in synthesizing nanoparticles on a large scale, as they can be easily cultivated in both the laboratory and on an industrial scale. Fungal endophytes have a great capacity for bioaccumulation and bioreduction, in addition to being sources of secondary metabolites and active biomolecules that make them effective in obtaining nanoparticles (Gupta *et al*., 2020). Species known as Trichoderma manage to generate different metabolites such as pyrones, terpenes, diketopiperazine, enzymes, glycolipids and polyketides that can help in the synthesis of oxides (Nadeem *et al*., 2020). Some fungi species such as F. oxysporum secrete proteins, polymers and enzymes that help in the stability and yield of the formed nanoparticles (Gupta *et al*., 2020). Like bacteria, fungi use two pathways for synthesis: intracellular and extracellular. Works show that the intracellular synthesis route presents samples with smaller sizes and with a good dispersion compared to the extracellular route (Waris *et al*., 2021). However, the extracellular synthesis pathway has been widely used, in which the components to be used by the synthesis are secreted by the fungi and thus the obtainment takes place outside the cellular components of the fungus. Several fungi are reported in the literature on oxide synthesis, as can be seen in Table 3. Figure 3 lists the fungus species with the particle size and morphology.

Table 3. Green synthesis of metal oxides using fungi as a source.

Fungus	Oxide obtained	Particle size (nm)	Morphology	Reference
Lactobacillus plantarum	MgO	30	Cubic	(Mohanasrinivasan *et al*., 2018)
Aspergillus niger	MgO	43-91	Spherical	(Ibrahem *et al*., 2017)
Aspergillus niger SIM 1	Fe_3O_4	50	Spherical	(Abdeen *et al*., 2016)
Aspergillus niger	MgO	10-42	Nanorod	(Mohamed *et al*., 2019)
Fusarium keratoplasticum	MgO	3-38	Hexagonal	
Trichoderma asperellum	CuO	110	Spherical	(Saravanakumar *et al*., 2019)
Penicillium chrysogenum-Mediated	CuO	9.70	Spherical	(El-sayyad, 2019)
Botrytis cinerea	CuO	60-80	-	(Kovačec *et al*., 2017)
Aspergillus terreus for	CuO	15-75	-	(Mousa *et al*., 2020)
Penicillium chrysogenum	CuO	25-36	-	(El-batal *et al*., 2018)

Source: Authors.

Figure 3. Relationship between particle size and fungus species and morphology.



Source: Authors.

Kalpana *et al*. (2019) synthesized ZnO using *Aspergillus niger* as a culture and obtained particle sizes between 84-91 nm and spherical morphology, and verified its use in the removal of Bismarck's brown dye and its microbial activity. The synthesized nanoparticles proved to be effective in degradation in the treatment of Bismarck brown wastewater and an excellent microbial activity of 12 mm for *Staphylococcus aureus* and 10 mm for *E. coli*.

Fouda *et al*. (2018) synthesized ZnO with spherical morphology and an average size of 10-45 nm using the fungus *Aspergillus terréus*. Antibacterial tests and in vitro cytotoxicity of biosynthesized ZnO were performed, and concluded that the nanoparticles had better inhibitory action against *Staphylococcus aureus* and *Bacillus subtilis* (Gram positive) bacteria than *Pseudomonas aeruginosa* and *Escherichia coli* (Gram negative).

According to Table 3 and Figure 3, it is possible to observe that the main oxides synthesized using fungi were MgO and CuO, as they exhibit excellent physical-chemical properties such as: corrosion resistance, low electrical conductivity, physical resistance, and mechanical strength, etc., and they are applied in several areas. It is also possible to notice that there is a variation in morphology for MgO from cubic to spherical, nanorod, hexagonal when using the *Lactobacillus plantarum*, *Aspergillus niger*, *Aspergillus niger* and *Fusarium keratoplasticum* fungi, respectively. This is due to the difference in the chemical composition present in the extract and also its synthesis route. However, CuO did not exhibit this variation in its morphology, only in crystallite size variation.

4. Final Considerations

The oxides obtained through conventional routes are used in several applications, but these synthesis routes are not ecological since there is the use of toxic reagents as well as the production of by-products that are harmful to the ecosystem due to their toxicity and harmful to human health. Given this scenario, green synthesis is a route that has been presenting itself as an excellent viable and ecologically friendly proposal for producing metallic oxides. Furthermore, it explores the chemical potential of plant phytochemicals in forming and improving the physicochemical properties of the synthesized products. Thus, green synthesis has shown considerable expansion due to these factors, as it provides adequate solutions to eliminate the problems (use of harmful reagents and production of toxic by-products) generated by conventional routes. As it is still a relatively new synthesis, there is a wide variety of methodologies used to obtain the material under study. Thus, this review comprehensively provides the main oxides synthesized in recent years and the use of different extract sources in the morphology and size of the particles generated. Therefore, this paper will significantly contribute to the national and international scientific literature, bringing a more specific material for researchers seeking to elaborate their projects on the green synthesis of metallic oxides.

Acknowledgments

This study was partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance code 001 and Edital n° 13/2020 PDPG – Amazônia-Legal. The authors acknowledge the CAPES and IFMA organs for the financial support used in performing this work.

References

Aarthye, P., & Sureshkumar, M. (2021). Green synthesis of nanomaterials: An overview. *Materials Today: Proceedings,* 10.1016/j.matpr.2021.04.564.

Abdeen, M., Sabry, S., Ghozlan, H., El-Gendy, A. A., & Carpenter, E. E. (2016). Microbial-Physical Synthesis of Fe and Fe3O4 Magnetic Nanoparticles Using Aspergillus Niger YESM1 and Supercritical Condition of Ethanol. *Journal of Nanomaterials,* 2016. 10.1155/2016/9174891

Abinaya, S., Kavitha, H. P., Prakash, M., & Muthukrishnaraj, A. (2021). Green synthesis of magnesium oxide nanoparticles and its applications: A review. *Sustainable Chemistry and Pharmacy*, 19(September 2020), 100368. 10.1016/j.scp.2020.100368

Akintelu, S. A., Folorunso, A. S., Folorunso, F. A., & Oyebamiji, A. K. (2020). Green synthesis of copper oxide nanoparticles for biomedical application and environmental remediation. *Heliyon*, 6(7), e04508. 10.1016/j.heliyon.2020.e04508

Alasvand, K., & Ravishankar, Z. V. (2016). Inhibition of a sulfate reducing bacterium, Desulfovibrio marinisediminis GSR3, by biosynthesized copper oxide nanoparticles. *3 Biotech*, 6(1), 1–7. 10.1007/s13205-016-0403-0

Balraj, B., Senthilkumar, N., Siva, C., Krithikadevi, R., Julie, A., Potheher, I. V., & Arulmozhi, M. (2017). Synthesis and characterization of Zinc Oxide nanoparticles using marine Streptomyces sp. with its investigations on anticancer and antibacterial activity. *Research on Chemical Intermediates*, 43(4), 2367–2376. 10.1007/s11164-016-2766-6

Bandeira, M., Giovanela, M., Roesch-Ely, M., Devine, D. M., & da Silva Crespo, J. (2020). Green synthesis of zinc oxide nanoparticles: A review of the synthesis methodology and mechanism of formation. *Sustainable Chemistry and Pharmacy*, 15, 100223. 10.1016/j.scp.2020.100223.

Bibi, I., Nazar, N., Ata, S., Sultan, M., Ali, A., Abbas, A., Jilani, K., Kamal, S., Sarim, F. M., Khan, M. I., Jalal, F., & Iqbal, M. (2019). Green synthesis of iron oxide nanoparticles using pomegranate seeds extract and photocatalytic activity evaluation for the degradation of textile dye. *Journal of Materials Research and Technology*, 8(6), 6115–6124. 10.1016/j.jmrt.2019.10.006

Chen, L., Batjikh, I., Hurh, J., Han, Y., Huo, Y., Ali, H., Li, J. F., Rupa, E. J., Ahn, J. C., Mathiyalagan, R., & Yang, D. C. (2019). Green synthesis of zinc oxide nanoparticles from root extract of Scutellaria baicalensis and its photocatalytic degradation activity using methylene blue. *Optik*, 184(January), 324–329. 10.1016/j.ijleo.2019.03.051

Chinnasamy, C., Tamilselvam, P., Karthick, B., Sidharth, B., & Senthilnathan, M. (2018). Green Synthesis, Characterization and Optimization Studies of Zinc Oxide Nano Particles Using Costusigneus Leaf Extract. *Materials Today: Proceedings*, 5(2), 6728–6735. 10.1016/j.matpr.2017.11.331.

Das, K. R., Kowshik, M., Praveen Kumar, M. K., Kerkar, S., Shyama, S. K., & Mishra, S. (2018). Native hypersaline sulphate reducing bacteria contributes to iron nanoparticle formation in saltpan sediment: A concern for aquaculture. *Journal of Environmental Management,* 206, 556–564. 10.1016/j.jenvman.2017.10.078

Das, R. K., & Brar, S. K. (2013). Plant mediated green synthesis: Modified approaches. *Nanoscale*, 5(21), 10155–10162. 10.1039/c3nr02548a

Devatha, C. P., Jagadeesh, K., & Patil, M. (2018). Environmental Nanotechnology, Monitoring & Management E ff ect of Green synthesized iron nanoparticles by Azardirachta Indica in di ff erent proportions on antibacterial activity. *Environmental Nanotechnology, Monitoring & Management*, 9, 85–94. 10.1016/j.enmm.2017.11.007

Dubey, S., Kumar, J., Kumar, A., & Sharma, Y. C. (2018). Facile and green synthesis of highly dispersed cobalt oxide (Co3O4) nano powder: Characterization and screening of its eco-toxicity. *Advanced Powder Technology*, 29(11), 2583–2590. 10.1016/j.apt.2018.03.009

Dutta, S., Jaiswal, K. K., Verma, R., Basavaraju, D. M., & Ramaswamy, A. P. (2019). Green synthesis of zinc oxide catalyst under microwave irradiation using banana (Musa spp.) corm (rhizome) extract for biodiesel synthesis from fish waste lipid. *Biocatalysis and Agricultural Biotechnology,* 22, 101390. 10.1016/j.bcab.2019.101390

El-batal, A. I., Al-hazmi, N. E., Mosallam, F. M., & El-sayyad, G. S. (2018). Microbial Pathogenesis Biogenic synthesis of copper nanoparticles by natural polysaccharides and Pleurotus ostreatus fermented fenugreek using gamma rays with antioxidant and antimicrobial potential towards some wound pathogens. *Microbial Pthogenesis*, 118(March), 159–169. 10.1016/j.micpath.2018.03.013

El-sayyad, A. I. E. G. S. (2019). Penicillium chrysogenum -Mediated Mycogenic Synthesis of Copper Oxide Nanoparticles Using Gamma Rays for In Vitro Antimicrobial Activity Against Some Plant Pathogens. *Journal of Cluster Science,* 3. 10.1007/s10876-019-01619-3

Eltarahony, M., Zaki, S., & Abd-el-haleem, D. (2018). Concurrent Synthesis of Zero- and One-Dimensional, Spherical, Rod, Needle, and Wire-Shaped CuO *Nanoparticles by Proteus mirabilis* 10B. 2018.

Fazlzadeh, M., Rahmani, K., Zarei, A., Abdoallahzadeh, H., Nasiri, F., & Khosravi, R. (2017). A novel green synthesis of zero valent iron nanoparticles (NZVI) using three plant extracts and their efficient application for removal of Cr (VI) from aqueous solutions. *Advanced Powder Technology,* 28(1), 122–130. 10.1016/j.apt.2016.09.003

Fink, A. (2019). Conducting Research Literature Reviews: From the Internet to Paper (SAGE Publi).

Fouda, A., EL-Din Hassan, S., Salem, S. S., & Shaheen, T. I. (2018). In-Vitro cytotoxicity, antibacterial, and UV protection properties of the biosynthesized Zinc oxide nanoparticles for medical textile applications. *Microbial Pathogenesis,* 125(September), 252–261. 10.1016/j.micpath.2018.09.030

Ghasemi, N., Jamali-sheini, F., & Zekavati, R. (2017). CuO and Ag / CuO nanoparticles: Biosynthesis and antibacterial properties. *Materials Letters,* 196, 78–82. 10.1016/j.matlet.2017.02.111

Gowri, M., Latha, N., & Rajan, M. (2019). Copper Oxide Nanoparticles Synthesized Using Eupatorium odoratum, Acanthospermum hispidum Leaf Extracts, and Its Antibacterial Effects Against Pathogens: a Comparative Study. *BioNanoScience,* 9(3), 545–552. 10.1007/s12668-019-00655-7

Gupta, K., & Chundawat, T. S. (2020). Zinc oxide nanoparticles synthesized using Fusarium oxysporum to enhance bioethanol production from rice-straw. *Biomass and Bioenergy,* 143(July), 105840. 10.1016/j.biombioe.2020.105840

Hulkoti, N. I., & Taranath, T. C. (2014). Biosynthesis of nanoparticles using microbes-A review. Colloids and Surfaces B: *Biointerfaces*, 121, 474–483. 10.1016/j.colsurfb.2014.05.027

Ibrahem, E., Thalij, K., & Badawy, A. (2017). Antibacterial Potential of Magnesium Oxide Nanoparticles Synthesized by Aspergillus niger. *Biotechnology Journal International*, 18(1), 1–7. 10.9734/bji/2017/29534

Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13(10), 2638–2650. 10.1039/c1gc15386b

Jacob, P. J., Masarudin, M. J., Hussein, M. Z., & Rahim, R. A. (2019). Optimization of process parameters in fl uencing the sustainable construction of iron oxide nanoparticles by a novel tropical wetlands. *Journal of Cleaner Production,* 232, 193–202. 10.1016/j.jclepro.2019.05.359

Jeevanandam, J., Chan, Y. S., & Danquah, M. K. (2017). Biosynthesis and characterization of MgO nanoparticles from plant extracts via induced molecular nucleation. *New Journal of Chemistry*, 41(7), 2800–2814. 10.1039/c6nj03176e

Kalpana, V. N., Kataru, B. A. S., Sravani, N., Vigneshwari, T., Panneerselvam, A., & Devi Rajeswari, V. (2018). Biosynthesis of zinc oxide nanoparticles using culture filtrates of Aspergillus niger: Antimicrobial textiles and dye degradation studies. OpenNano, 3(June), 48–55. 10.1016/j.onano.2018.06.001
Karpagavinayagam, P., & Vedhi, C. (2019). Green synthesis of iron oxide nanoparticles using Avicennia marina flower extract. Vacuum, 160(12159), 286–292. 10.1016/j.vacuum.2018.11.043

Khan, Z. U. H., Sadiq, H. M., Shah, N. S., Khan, A. U., Muhammad, N., Hassan, S. U., Tahir, K., safi, S. Z., Khan, F. U., Imran, M., Ahmad, N., Ullah, F., Ahmad, A., Sayed, M., Khalid, M. S., Qaisrani, S. A., Ali, M., & Zakir, A. (2019). Greener synthesis of zinc oxide nanoparticles using Trianthema portulacastrum extract and evaluation of its photocatalytic and biological applications. *Journal of Photochemistry and Photobiology B: Biology*, 192(November 2018), 147–157. 10.1016/j.jphotobiol.2019.01.013

Khatami, M., Alijani, H. Q., Heli, H., & Sharifi, I. (2018). Rectangular shaped zinc oxide nanoparticles: Green synthesis by Stevia and its biomedical efficiency. Ceramics International, 44(13), 15596–15602. 10.1016/j.ceramint.2018.05.224

Kouhkan, M., Ahangar, P., Babaganjeh, L. A., & Allahyari-devin, M. (2020). Biosynthesis of Copper Oxide Nanoparticles Using. 101–111. 10.2174/1573413715666190318155801

Kovačec, E., Regvar, M., van Elteren, J. T., Arčon, I., Papp, T., Makovec, D., & Vogel-Mikuš, K. (2017). Kovačec2017.pdf. Chemosphere Journal, 180, 178–185.

Kumar, B. P., Arthanareeswari, M., Devikala, S., Sridharan, M., Arockia selvi, J., & Pushpa malini, T. (2019). Green synthesis of zinc oxide nanoparticles using typha latifolia. L leaf extract for photocatalytic applications. Materials Today: Proceedings, 14, 332–337. 10.1016/j.matpr.2019.04.155

Lu, J., Ali, H., Hurh, J., Han, Y., Batjikh, I., Rupa, E. J., Anandapadmanaban, G., Park, J. K., & Yang, D. C. (2019). The assessment of photocatalytic activity of zinc oxide nanoparticles from the roots of Codonopsis lanceolata synthesized by one-pot green synthesis method. Optik, 184(March), 82–89. 10.1016/j.ijleo.2019.03.050

Lüdke, M., & André, M. E. D. A. (2012). *Pesquisa em educação: abordagens qualitativas* (E.P.U).

Maruthupandy, M., Zuo, Y., Chen, J. S., Song, J. M., Niu, H. L., Mao, C. J., Zhang, S. Y., & Shen, Y. H. (2017). Synthesis of metal oxide nanoparticles (CuO and ZnO NPs) via biological template and their optical sensor applications. *Applied Surface Science*, 397, 167–174. 10.1016/j.apsusc.2016.11.118

Moghaddas, T. H. S. M., Elahi, B., Darroudi, M., & Javanbakht, V. (2019). Green synthesis of hexagonal-shaped zinc oxide nanosheets using mucilage from flaxseed for removal of methylene blue from aqueous solution. *Journal of Molecular Liquids*, 296, 111834. 10.1016/j.molliq.2019.111834

Mohamed, A. A., Fouda, A., Abdel-Rahman, M. A., Hassan, S. E. D., El-Gamal, M. S., Salem, S. S., & Shaheen, T. I. (2019). Fungal strain impacts the shape, bioactivity and multifunctional properties of green synthesized zinc oxide nanoparticles. *Biocatalysis and Agricultural Biotechnology*, 19(January), 101103. 10.1016/j.bcab.2019.101103

Mohanasrinivasan, V., Subathra Devi, C., Mehra, A., Prakash, S., Agarwal, A., Selvarajan, E., & Jemimah Naine, S. (2018). Biosynthesis of MgO Nanoparticles Using Lactobacillus Sp. and its Activity Against Human Leukemia Cell Lines HL-60. *BioNanoScience*, 8(1), 249–253. 10.1007/s12668-017-0480-5

Moraes, L. C., Figueiredo, R. C., Ribeiro-andrade, R., Arantes, L., Giani, A., Figueredo, C. C., & Pontes-silva, A. V. (2021). High diversity of microalgae as a tool for the synthesis of different silver nanoparticles*: A species-specific green synthesis*. 42(May). 10.1016/j.colcom.2021.100420

Mousa, A. M., Abdel, O. A., Al-hagar, O. E. A., Gizawy, M. A., Allan, K. F., & Attallah, M. F. (2020). Biosynthetic new composite material containing CuO nanoparticles produced by Aspergillus terreus for 47 Sc separation of cancer theranostics application from irradiated Ca target. *Applied Radiation and Isotopes*, 166(July), 109389. 10.1016/j.apradiso.2020.109389

Muthuvinothini, A., & Stella, S. (2019). Green synthesis of metal oxide nanoparticles and their catalytic activity for the reduction of aldehydes. *Process Biochemistry*, 77(July 2018), 48–56. 10.1016/j.procbio.2018.12.001

Nadeem, M., Khan, R., Afridi, K., Nadhman, A., Ullah, S., & Faisal, S. (2020). Green Synthesis of Cerium Oxide Nanoparticles (CeO 2 NPs) and Their Antimicrobial Applications : A Review. *International Journal of Nanomedicine*, 15, 5951–5961.

Narendhran, S., Manikandan, M., & Baby Shakila, P. (2019). Antibacterial, antioxidant properties of Solanum trilobatum and sodium hydroxide-mediated magnesium oxide nanoparticles: *A green chemistry approach. Bulletin of Materials Science*, 42(3). 10.1007/s12034-019-1811-7

Nasrollahzadeh, M., Sajadi, S. M., Rostami-Vartooni, A., & Hussin, S. M. (2016). Green synthesis of CuO nanoparticles using aqueous extract of Thymus vulgaris L. leaves and their catalytic performance for N-arylation of indoles and amines. *Journal of Colloid and Interface Science*, 466, 113–119. 10.1016/j.jcis.2015.12.018

Nisha, B., Vidyalakshmi, Y., & Razack, S. A. (2020). Enhanced formation of ruthenium oxide nanoparticles through green synthesis for highly efficient supercapacitor applications. *Advanced Powder Technology*, 31(3), 1001–1006. 10.1016/j.apt.2019.12.026

Olajire, A. A., & Mohammed, A. A. (2020). Green synthesis of nickel oxide nanoparticles and studies of their photocatalytic activity in degradation of polyethylene films. *Advanced Powder Technology*, 31(1), 211–218. 10.1016/j.apt.2019.10.012

Ramalingam, R., Fazil, M. H. U. T., Verma, N. K., & Arunachalam, K. D. (2019). Green synthesis, characterization and antibacterial evaluation of electrospun nickel oxide nanofibers. *Materials Letters*, 256, 126616. 10.1016/j.matlet.2019.126616

Ramanarayanan, R., Bhabhina, N. M., Dharsana, M. V., Nivedita, C. V., & Sindhu, S. (2018). Green synthesis of zinc oxide nanoparticles using extract of Averrhoa bilimbi(L) and their photoelectrode applications. Materials Today: *Proceedings*, 5(8), 16472–16477. 10.1016/j.matpr.2018.05.150

Rao, T. N., Riyazuddin, Babji, P., Ahmad, N., Khan, R. A., Hassan, I., Shahzad, S. A., & Husain, F. M. (2019). Green synthesis and structural classification of Acacia nilotica mediated-silver doped titanium oxide (Ag/TiO2) spherical nanoparticles: Assessment of its antimicrobial and anticancer activity. *Saudi Journal of Biological Sciences*, 26(7), 1385–1391. 10.1016/j.sjbs.2019.09.005

Rehana, D., Mahendiran, D., Kumar, R. S., & Rahiman, A. K. (2017). Evaluation of antioxidant and anticancer activity of copper oxide nanoparticles synthesized using medicinally important plant extracts. *Biomedicine and Pharmacotherapy*, 89, 1067–1077. 10.1016/j.biopha.2017.02.101

Saravanakumar, K., Shanmugam, S., & Babu, N. (2019). Journal of Photochemistry & Photobiology , B : Biology Biosynthesis and characterization of copper oxide nanoparticles from indigenous fungi and its effect of photothermolysis on human lung carcinoma. *Journal of Photochemistry & Photobiology, B: Biology*, 190(June 2018), 103–109. 10.1016/j.jphotobiol.2018.11.017

Shaaban, M., & El-Mahdy, A. M. (2018). Biosynthesis of Ag, Se, and ZnO nanoparticles with antimicrobial activities against resistant pathogens using waste isolate Streptomyces enissocaesilis. *IET Nanobiotechnology*, 12(6), 741–747. 10.1049/iet-nbt.2017.0213

Shamaila, S., Sajjad, A. K. L., Ryma, N. ul A., Farooqi, S. A., Jabeen, N., Majeed, S., & Farooq, I. (2016). Advancements in nanoparticle fabrication by hazard free eco-friendly green routes. *Applied Materials Today*, 5, 150–199. 10.1016/j.apmt.2016.09.009

Shanmugasundaram, T., & Balagurunathan, R. (2017). Bio-medically active zinc oxide nanoparticles synthesized by using extremophilic actinobacterium, Streptomyces sp. (MA30) and its characterization. *Artificial Cells, Nanomedicine and Biotechnology*, 45(8), 1521–1529. 10.1080/21691401.2016.1260577

Soto-Robles, C. A., Luque, P. A., Gómez-Gutiérrez, C. M., Nava, O., Vilchis-Nestor, A. R., Lugo-Medina, E., Ranjithkumar, R., & Castro-Beltrán, A. (2019). Study on the effect of the concentration of Hibiscus sabdariffa extract on the green synthesis of ZnO nanoparticles. *Results in Physics*, 15(September). 10.1016/j.rinp.2019.102807

Srinivasan, M., Venkatesan, M., Arumugam, V., Natesan, G., Saravanan, N., Murugesan, S., Ramachandran, S., Ayyasamy, R., & Pugazhendhi, A. (2019). Green synthesis and characterization of titanium dioxide nanoparticles (TiO 2 NPs) using Sesbania grandiflora and evaluation of toxicity in zebrafish embryos. *Process Biochemistry*, 80(February), 197–202. 10.1016/j.procbio.2019.02.010

Subhapriya, S., & Gomathipriya, P. (2018). Green synthesis of titanium dioxide (TiO2) nanoparticles by Trigonella foenum-graecum extract and its antimicrobial properties. *Microbial Pathogenesis*, 116(January), 215–220. 10.1016/j.micpath.2018.01.027

Thatoi, P., Kerry, R. G., Gouda, S., Das, G., Pramanik, K., Thatoi, H., & Patra, J. K. (2016). Photo-mediated green synthesis of silver and zinc oxide nanoparticles using aqueous extracts of two mangrove plant species, Heritiera fomes and Sonneratia apetala and investigation of their biomedical applications. *Journal of Photochemistry and Photobiology B: Biology*, 163, 311–318. 10.1016/j.jphotobiol.2016.07.029

Vinayagam, R., Selvaraj, R., Arivalagan, P., & Varadavenkatesan, T. (2020). Synthesis, characterization and photocatalytic dye degradation capability of Calliandra haematocephala-mediated zinc oxide nanoflowers. *Journal of Photochemistry and Photobiology B: Biology*, 203(October 2019), 111760. 10.1016/j.jphotobiol.2019.111760

Waris, A., Din, M., Ali, A., Ali, M., Afridi, S., & Baset, A. (2021). A comprehensive review of green synthesis of copper oxide nanoparticles and their diverse biomedical applications. *Inorganic Chemistry Communications*, 123, 108369. 10.1016/j.inoche.2020.108369