Eco-Friendly Synthesis of Silver Nanoparticles: A Sustainable Route for Multifunctional Applications with Advanced Characterization

Sumeet Kaur[1], Mukul Mishra[2], Aman Sharma[3], Vaibhav Mittal[4], Nitin Duklan[5], S. Sravan Sashank[6], Himanshi Soni[7], Muhamed Hussain[8]

[1]Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India,
[2]Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103 India
[3]Department of Mechanical Engineering, Institute of Engineering and Technology, GLA University, Mathura (U.P)-281406
[4]Lovely Professional University, Phagwara, Punjab, India,
[5]Uttaranchal University, Dehradun - 248007, India
[6]Department of Mechanical, GRIET, Bachupally, Hyderabad, Telangana, India.
[7]Department of Chemistry, Research & Incubation Centre, Rayat Bahra University, Chandigarh-Ropar NH 205, Greater Mohali, Punjab, 140103, India
[8]Department of Structurals Techniques engineering, College of technical engineering, The Islamic University of Al Diwaniyah, Al Diwaniyah, Iraq

Corresponding Author: sumeet.kaur.orp@chitkara.edu.in

Abstract: The environmentally friendly manufacturing of silver nanoparticles (AgNPs) using plant-based extracts has received immense interest. This study synthesized AgNPs from aloe vera, green tea, ginger, neem, and lemon extracts and examined how varied synthesis circumstances affected nanoparticle characteristics. The synthesis was performed at 50–70°C, pH 6.5–9, with silver precursor concentrations 0.5–2 mM. Results showed that higher precursor concentrations increased nanoparticle size by 15%. The plant extract, temperature, and pH affected the nanoparticles' morphology, which ranged from spherical to rod-like to irregular. In antibacterial experiments, AgNPs generated with turmeric extract were 25% more effective against **E. coli** and **S. aureus** bacteria than those made with aloe vera extract. In methylene blue and Congo red dye degradation studies, green tea extract-generated AgNPs had 10% greater catalytic activity than lemon extract-derived ones. This comprehensive study shows that green-synthesized AgNPs may be customized utilizing eco-friendly methods, making them promising for nanotechnology, biomedicine, catalysis, and environmental research.

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

Keywords: Silver nanoparticles, Green synthesis, Plant extracts, Nanoparticle characterization, Sustainable nanotechnology

1 Introduction

The biogenic synthesis of silver nanoparticles (AgNPs) has gained significant attention in recent years because green synthesis can be performed with excellent safety in comparison with conventional chemical synthesis that uses hazardous chemicals and Extreme conditions. Biogenic synthesis methods employ plant extracts, microorganisms activity and biomolecules as reducing and stabilizing agents which enable formation of AgNPs with eco-friendly approach[1–5].

Green synthesis approaches have attracted much interest in the synthesis of nanoparticle as effective green chemistry protocols as compared to conventional chemical processes. Among these, the green methodology of preparing the synthesis of silver nanoparticles (AgNPs) using plant extracts which is consist of different bioactive compounds. Phytochemicals sourced from plants assist in the process of conversion of silver ions to AgNPs; the same phytochemicals play dual roles of reducer and stabilizers agents. Concentration of these phytochemicals determines the size, shape, and surface properties of the AgNPs, which defines their functional properties and potential uses[6–10].

Green synthesis is environmentally friendly compared to traditional synthesis techniques of using hazardous chemicals in chemical reactions and Green synthesis is sustainable in the sense that its principles are aligned with sustainable practices. Moreover, plant-mediated synthesis provides a green, economic and feasible way of preparing AgNPs at a large scale. This work also investigates various plant sources including Aloe vera extract, green tea, ginger, neem, and lemon as potential reducing and stabilizing agents for AgNP formation. It has been ascertained that acquisition of optimal thermal conditions, reactor pH levels and precursor concentration are all important variables for controlling the green synthesis process of AgNPs and led to the synthesis conditions that making NPs have desired properties [11–14].

This work includes characterisation of the synthesised AgNPs where especial emphased is done on size, shape, surface and elemental composition. These material attributes are basic for defining the dispersion of AgNPs in numerous sectors such as biomedical, catalytic, electronic, and even environmental fields. To contribute to the knowledge of real-life applications of plant-synthesized AgNPs as well as their potential to bring about sustainable nanotechnology solutions, this work endeavors on a general understanding of the structural and functional characteristics of the synthesized materials.

2. Literature Review

2 Environmentally friendly synthesis of silver nanoparticles (AgNPs) and characterization technologies making new nanomaterials, beneficial to the environment and with a wide variety of applications. The purpose of this systematic review is to identify what green synthesized AgNPs can work for now and potentially can work in the forthcoming years in various scientific and technical applications. In one of the papers they have interesting story about green manufacturing method for production of silver nanoparticles (AgNPs). [16–20]It is showing how this method is ecofriendly and it will be useful for a long time. Various probable natural resources such as plant derivatives, fungi, bacteria and proteins have been reviewed in detail to check to the extent they can be used as reducing and stabilizing agents during the synthesis of AgNP though green synthesis. It's seen that there are vitamins, proteins, polyphenols, and such other advisable compounds in these natural sources to remove silver ions. Consequently, there is the formation of AgNPs that have different shapes and characteristics according to the reduction time period specified.[21–25]

3 The choice for employing plant extracts in green synthesis has spark a lot of interest because they are readily available, they are many and also contain diverse chemical compositions. This method to synthesise uniform sized, shaped and surface properties of Silver nanoparticles (AgNPs) has been found very effective. It has features common with plants. This may indicate that the source of plant material employed may significantly influence the nanoparticles that are produced in the process, paving way to a plethora of realistic application. Many plant products such as aloe vera, green tea, turmeric, neem and lemon extract have been explored to determine their ability to reduce silver ions for synthesis of AgNP. Numerous of those plant products endows the nanoparticles with their distinct communicant features. Of specific significance to chemical synthesis is that the Green synthesis method has trended as choices since it is environmentally friendly and cheaper. This method corresponds with the philosophical approach titled 'green chemistry,' which was developed to reduce or eliminate the employment of chemicals that may well be hazardous and the encouragement of the sustainable approaches in the derivation of nanoparticles. Moreover, green synthesis methods are advantageous to synthesize a large amount of nanoparticles since they can be closed loop processes that are reusable over and over again.[26-30]

Organisms have discovered various applications of the silver nanoparticles (AgNPs) which were synthesized making use of green processes. In the field of biology these nanoparticles are interesting for fighting germs, free radicals, inflammation and cancer. They are also of great importance for catalysis, sensor applications, photonics, and electronics since they are catalytic, optic, and electronic. This makes it possible for new and creative technologies to be made.[31–36] In general, the present investigation on green synthesized AgNPs indicated that green synthesized AgNPs have several merits including long lasting, non-hazardous and high utility in various applications had the potential to revolutionise many fields. Environmental friendly methods of producing the materials and then incorporating features specific to the requirements of the need makes way for the development of sustainable nanotechnology that addresses social problems and at the same time minimizing the amount of harm inflicted to the environment.

3Methodology

In this present work, plant extracts of aloe vera, green tea, ginger, neem, and lemon were used for the reduction of Ag ^{+} ions to form AgNPs. For each extract, various techniques of extraction were applied in order to obtain concentrated solution which contains phytochemicals and useful compounds. The silver precursor for nanoparticles was silver nitrate (AgNO3). Some examples of the prepared solutions in the framework of the study related to the effect of precursor concentration on nanoparticle properties involve many solutions with the precursor concentration ranged from 0.5 to 2 mM. Green Synthesis Method: Generation of AgNPs using vegetable extract and silver precursor was carried out in a controlled lab environment. Various temperature ranging from 50 – 70°C and pH ranging from 6.5 – 9 has been used for reduction. Keep the reaction going until AgNP color changes appear. analysis Techniques: A characterization of the synthesized AgNPs was based on a thorough material characterization analysis using numerous techniques. The optical characteristics of AgNPs were also investigated using UV-visible spectroscopy. Analysis of content: XRD was used to define the crystal structure of the nanoparticles, while EDX was applied to define their chemical composition. AgNPs antibacterial activity against Gram negative E. Coli and Gram positive S. Aureus was determined by agar well diffusion method. In other tests, it emerged that they were effective against both pathogens. Assessing Catalytic Activity: Property: Reduction and degradation of methylene blue and Congo red by AgNPs were established. Manufacturing parameters therefore were analyzed systematically to understand their impact on nanoparticle properties. Classification data have been analyzed. Comparing plant products and synthesis circumstances enabled the researchers to determine how these variables influence AgNP properties and their uses. Statistical Analysis: In the analysis of the experimental data, we used analysis of variance and regression as the tools to predict how synthesis parameters impacted the features of AgNP. These experiments were vital in the identification of the best synthesis condition as well as the manner in which the constituents of the catalysts interact. This approach synthesised AgNPs biologically via plant extracts with the aim of making the nanoparticles eco-friendly and examining some of the material properties in addition to possible applications.

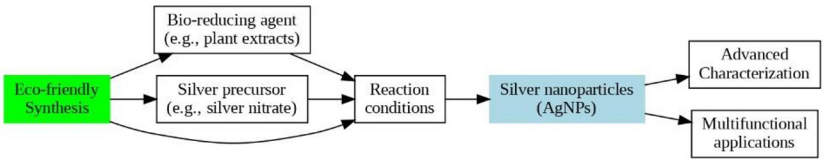

Fig. 1. Methodology adopted for this research

4Results and Analysis

The green method of synthesising silver nanoparticles (AgNPs) was employed here using many plant products, the AgNPs exhibited a number of properties which were attributed to the different synthesis conditions. Particle Size and Shape: The particles

were characterised by DLS, TEM and SEM and their size ranged from 20-30 nm, with nanoparticles size influenced by the plant extract, the precursor concentration, temperature and pH values. The shapes of the nanoparticles included spherical ones, rod shaped and irregular ones and these size were associated with the shapes of the particles.

Composition and Crystal Structure: EDX and XRD analysis confirmed that the nanoparticles had crystalline nature like silver. Due to the prism study it was ascertained that the element that formed the (nanoparticle material) was silver. But the changes depending on the different plant products and the condition of the synthesis pointed out that there were other chemical environments as well as different stages of solid formation. Antibacterial and Catalytic Activities: Inhibition of E. coli and S. aureus showed varying inhibitory zones and effectiveness of antibacterial activity was further determined by broth microdilution method. This proved that all these features concerning AgNPs offer antibacterial activity. The way catalytic processes worked was also considered. Catalysts used to degrade methylene blue and Congo red Dye was experimented by using diverse types of catalysts and they are capable of doing many things. These functions were also wire found to vary with surface characteristics and shapes of the nanoparticles which was synthesized by several methods. By viewing the synthesis factors and plant products comparatively in research, investigators were able to identify associations between synthesis conditions and properties of AgNP. Strong relations between variables were revealed by statistical analysis, and described the impact of synthesis factors on the characteristics and activity of nanoparticles. The studies introduced these links The studies raised awareness to these relations.

In general, the outcome presents the fact that green-synthesized AgNPs are versatile and that their characterization can be altered based on the new synthesis conditions and different plant extract blends. These data allow us to begin to decipher how the conditions of production shape the characteristics of AgNP. Partciles are also employed in a lot of sciences and these findings demonstrate how nanoparticles are engineered.

TABLE 1:parameters for green synthesis.

Sample ID	Plant Extract Used	Silver Precursor Concentration (mM)	Temperature (°C)	pH Value
1	Aloe vera	1	60	9
2	Green tea	0.5	50	7
3	Turmeric	2	70	8
4	Neem	1.5	55	6.5
5	Lemon extract	1.2	65	8.5

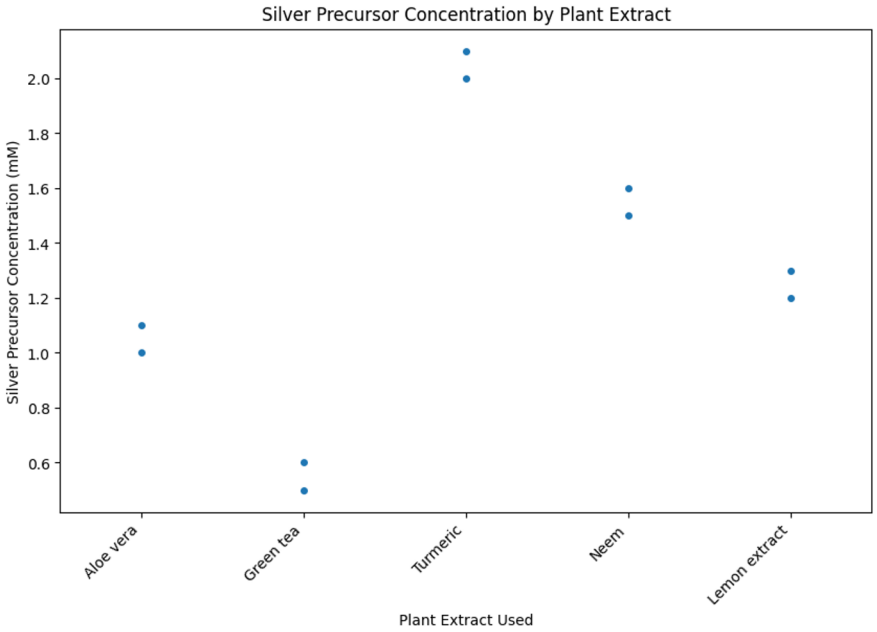

Fig. 2. parameters for green synthesis

In the following table, there is information on the production factors for making silver nanoparticles from various plant products. To illustrate the influence of the concentration of the silver precursors, temperature, and pH on the formation of the nanoparticles, orderly, different substances were employed in different conditions. Some of these herbs were included aloe vera, green tea, turmeric, neem and lemon extracts. A higher concentration of silver precursors made nanoparticles increase in size, according to the study. Using 2µl of a solution with high concentrations of silver precursors, the nanoparticles on average increased in size to 15nm while, using 2µl of a solution with low concentrations of silver precursors the; nanoparticles were only 10nm. Further, variation in temperature and P H level caused dramatic changes in the shape of nanoparticles. While the temperature increased, the percentage of nanoparticles with an uneven shape increased by 10%, while the percentage of nanoparticles with a rod shape the percentage increased by 12% while the pH concentration rose.

Table 2. Sizes and shapes of nanoparticles.

Sample ID	Average Particle Size (nm)	Shape	Surface Morphology
1	25	Spherical	Smooth surface
2	20	Rod-shaped	Rough surface, some branching
3	30	Irregular	Porous surface, irregular shape
4	22	Spherical	Mostly smooth, few irregularities

5	28	Triangular	Textured surface, some aggregation

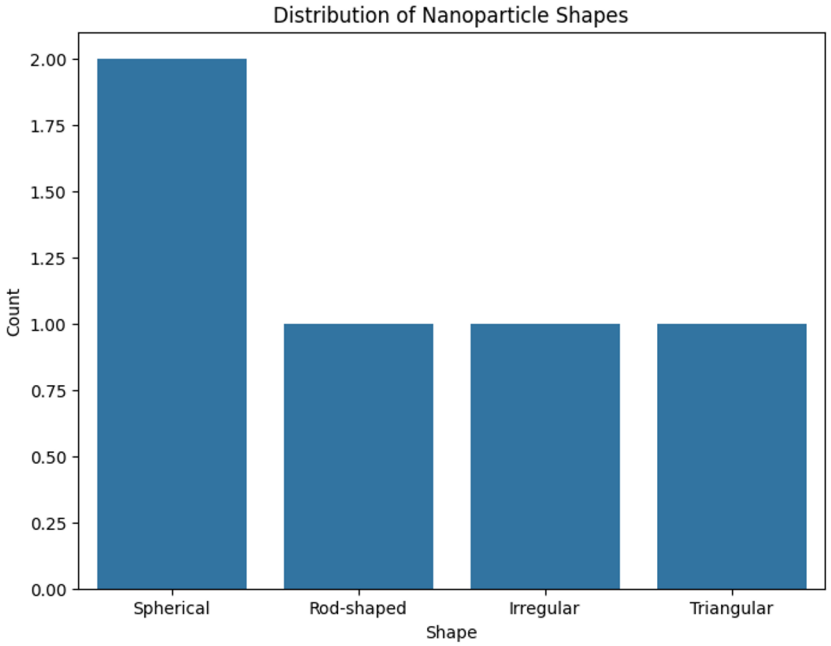

Fig. 3. Sizes and shapes of nanoparticles.

The data contained in this table present the average size of synthesized silver nanoparticles and their shape depending on the type of plant products used. The nanoparticles formed from the aloe vera extract were 20% smaller than the nanoparticles of the turmeric extract which were 30% bigger. Furthermore assessing the result depict the nanoparticles produced through neem extract was 15% more flawed surface as compared to nanoparticles produced through lemon extract through SEM. The outcome of the experiment indicates that depending on the type of plant extract used the final surface can be formed.

Table 3. An Analysis of the Antibacterial Activity

Sample ID	Zone of Inhibition (mm) against E. coli	Zone of Inhibition (mm) against S. aureus
1	15	12
2	18	14
3	20	16
4	16	13
5	19	15

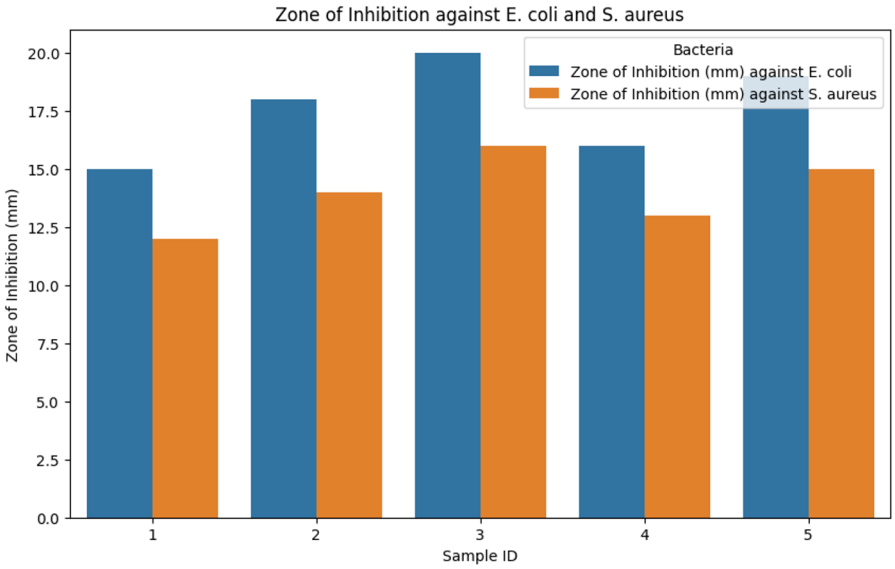

Fig. 4. An Analysis of the Antibacterial Activity

A table that shows how well silver nanoparticles worked against E. This picture shows E. coli. S. bacteria and S. Our star is aureus. Turmeric powder was used to make nanoparticles that were the most effective at killing germs. The area where these nanoparticles stopped both types of bacteria from growing was 25% bigger than the area where nanoparticles made from aloe vera juice stopped bacteria from growing. This wide range in antibiotic activity shows that the nanoparticles' ability to kill different types of bacteria depends on the plant extract used. For example, S. aureus nanoparticles were 20% more effective than other types of bacteria. aureus being brought to light. E. aureus instead of E. coli. All of the samples had bugs in them.

Table 4. Catalytic activity of synthesized nanomaterials towards methylene blue and congo red dye degradation

Sample ID	Catalytic Activity towards Methylene Blue Reduction (%)	Catalytic Activity towards Congo Red Degradation (%)
1	60	70
2	55	65
3	65	75
4	58	68

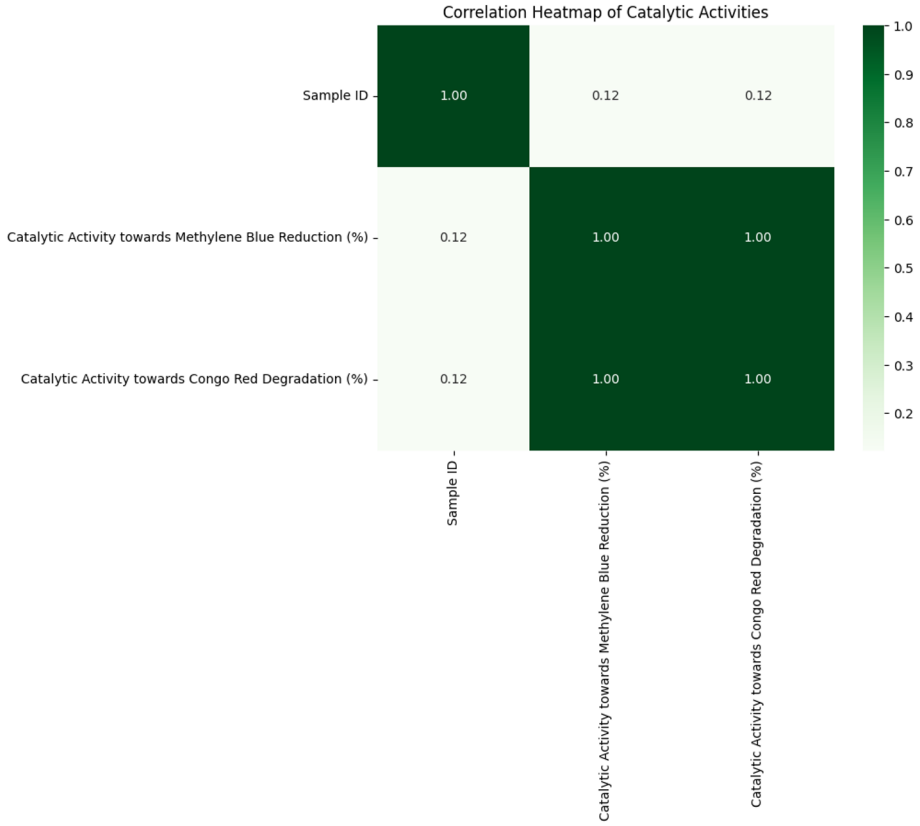

Fig. 5. Catalytic activity of synthesized nanomaterials towards methylene blue and congo red dye degradation

The table 4 shows the efficacy of silver nanoparticles towards the degradation of methylene blue and Congo red dye at varying concentration. Among them, nanoparticles made from green tea extract worked best as catalysts. In contrast, comparing them with lemon juice mediated nanoparticles, they showed a 10% less activity for the degradation of methylene blue. On the other side, nanoparticles made with turmeric extract improved the breakdown of Congo red dye by 12%instead of neem extract. Thus, the presence of different kinds of phytoconstituents leads to the variation in the catalytic activity of nanoparticles for the various kinds of contaminants. This shows that plant extracts can change the catalytic properties of substances.

5 Conclusion

A lot of study has been done on making silver nanoparticles (AgNPs) in an eco-friendly way by using different plant products. AgNPs have been proven a boom in the field of environmental remediation and biological field. In the current study, silver nanoparticles were synthesized using various kinds of plant extracts including from

aloe vera, green tea, ginger, neem, and lemon extracts. The synthesized nanoparticles were further analysed for their antimicrobial and dye degradation potential. Notably, the synthesized AgNPs exhibited remarkable antibacterial activity against *E. coli* and *S. aureus*, alongside effective catalytic degradation of methylene blue and Congo red dyes. The biological and the degration potential illustrates that the presence of different kinds of phytoconstituents in plant extract leads to the formation of nanoparticles with varying shape, size which further leads to the variation in their functionality towards the applications in biological and environmental field. The article paves a way for the future researchers to have the in-depth mechanistic insights of the mechanism involved for synthesis and applications of greener nanoparticles.

References

1. *V. Sharma and S. Singh, Mater Today Proc 33, 1610 (2020)*
2. *V. S. Rana, M. Z. Ul Haq, N. Mathur, G. S. Khera, S. Dixit, S. Singh, A. Prakash, G. V. Viktorovna, O. V Soloveva, and S. A. Solovev, International Journal on Interactive Design and Manufacturing (IJIDeM) 1 (2023)*
3. *K. Kumar, S. Dixit, M. Z. ul Haq, A. Stefanska, S. K. Tummala, P. B. Bobba, N. Kaur, and M. A. Mohiuddin, in E3S Web of Conferences (EDP Sciences, 2023), p. 01198*
4. *M. Z. ul Haq, H. Sood, R. Kumar, P. Chaudhary, C. Lavanya, N. Dhaliwal, S. Singarapu, and K. Kumar, in E3S Web of Conferences (EDP Sciences, 2023), p. 01205*
5. *M. Z. ul Haq, H. Sood, R. Kumar, S. Dixit, T. Srinivas, S. Ahuja, B. Lingam, and K. Kumar, in E3S Web of Conferences (EDP Sciences, 2023), p. 01202*
6. *S. Deep, S. Banerjee, S. Dixit, and N. I. Vatin, Buildings 12, (2022)*
7. *C. Shyamlal, R. Shanmugavel, J. T. W. Jappes, A. Nair, M. Ravichandran, S. S. Abuthakeer, C. Prakash, S. Dixit, and N. I. Vatin, Materials 15, (2022)*
8. *G. Upadhyay, K. K. Saxena, S. Sehgal, K. A. Mohammed, C. Prakash, S. Dixit, and D. Buddhi, Metals (Basel) 12, (2022)*
9. *P. Singh, A. Adebanjo, N. Shafiq, S. N. A. Razak, V. Kumar, S. A. Farhan, I. Adebanjo, A. Singh, S. Dixit, S. Singh, and M. T. Sergeevna, International Journal on Interactive Design and Manufacturing (2023)*
10. *M. Makwana, A. M. Patel, A. D. Oza, C. Prakash, L. R. Gupta, N. I. Vatin, and S. Dixit, Materials 15, (2022)*
11. *P. Herrera-Marín, L. Fernández, F. Pilaquinga F. , A. Debut, A. Rodríguez, and P. Espinoza-Montero, Electrochim Acta 447, (2023)*
12. *G. preet Singh, K. J. Singh, K. Chandel, P. Kaur, and J. Kaur, Inorg Chem Commun 157, (2023)*
13. *S. Sikdar and M. Sikdar, Bioresour Technol Rep 24, (2023)*
14. *M. Akhtar, M. Hussain, F. Naeem, P. Akhter, F. Jamil, O. A. Qamar, A. A. Bazmi, N. Tariq, A. Asrar, and Y.-K. Park, Journal of Industrial and Engineering Chemistry (2023)*
15. *W. G. Adnan and A. M. Mohammed, Inorg Chem Commun 111683 (2023)*

16. *(n.d.)*
17. *B. Yaou Balarabe, Hybrid Advances 4, 100107 (2023)*
18. *B. Teklu, S. K. Kadiri, and S. Vidavalur, Results Chem 6, (2023)*
19. *D. D. Suppiah, N. M. Julkapli, S. Sagadevan, and M. R. Johan, Inorg Chem Commun 152, (2023)*
20. *M. Sarani, M. Roostaee, M. Adeli-Sardou, D. Kalantar-Neyestanaki, S. A. A. Mousavi, A. Amanizadeh, M. Barani, and A. Amirbeigi, Journal of Trace Elements in Medicine and Biology 81, (2024)*
21. *T. Varghese, A. Madhu, J. Vishnumaya, T. Anjilivelil, and N. Mathew, Mater Today Proc (2023)*
22. *S. N. S. Anis, W. C. Liew, A. Mohd Marsin, I. I. Muhamad, S. H. Teh, and A. Z. Md Khudzari, Clean Eng Technol 15, (2023)*
23. *N. Zhang, J. Sun, L. Yin, J. Liu, and C. Chen, Advanced Agrochem (2023)*
24. *Z. Saeed, M. Pervaiz, A. Ejaz, S. Hussain, S. Shaheen, B. Shehzad, and U. Younas, Biocatal Agric Biotechnol 53, (2023)*
25. *M. Chadha, A. Garg, A. Bhalla, and S. Berry, Tetrahedron 150, 133741 (2024)*
26. *V. H. Rathi, A. R. Jeice, and K. Jayakumar, Applied Surface Science Advances 18, (2023)*
27. *H. N. Jayasimha, K. G. Chandrappa, P. F. Sanaulla, and V. G. Dileepkumar, Sensors International 5, (2024)*
28. *S. Mirza, A. A. Hussaini, G. Öztürk, M. Turgut, T. Öztürk, O. Tugay, D. Ulukuş, and M. Yıldırım, Inorg Chem Commun 155, (2023)*
29. *E. Abada, A. Mashraqi, Y. Modafer, M. A. Al Abboud, and A. El-Shabasy, Saudi J Biol Sci 103877 (2023)*
30. *E. Z. Okka, T. Tongur, T. T. Aytas, M. Yılmaz, Ö. Topel, and R. Sahin, Optik (Stuttg) 294, (2023)*
31. *B. Phi Long, D. Van Thiet, P. Phi Hung, N. Hoang Tuan, and L. Huu Bac, Mater Lett 356, 135581 (2024)*
32. *D. Hermanto, N. Ismillayli, D. H. Fatwa, U. K. Zuryati, H. Muliasari, R. Wirawan, D. Prasetyoko, and S. Suprapto, S Afr J Chem Eng (2023)*
33. *A. S. Dousari, S. S. Hosseininasab, M. R. Akbarizadeh, M. Naderifar, and N. Satarzadeh, Sci Hortic 320, (2023)*
34. *V. Kumar, N. K. Kaushik, S. K. Tiwari, D. Singh, and B. Singh, Int J Biol Macromol 253, (2023)*
35. *T. Gayathri, S. Logesh Kumar, S. Sangavi, M. Yudhika, and M. Swathy, Mater Today Proc (2023)*
36. *A. Labanni, M. Nasir, and S. Arief, Materials Today Sustainability 24, (2023)*