Chapter 26

Use of Nanoparticles against Salmonellosis in Poultry

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ABSTRACT

The infections are getting harder to treat day by day due to an increase in the prevalence of drug-resistant bacteria. The primary use of nanoparticles against infections is their role as an alternative to antibiotics for preventing antibiotic resistance. Along with antibiotic resistance, the other factors involved in their usage are enhanced potency and broad-spectrum activity. Various nanoparticles have shown a potential against bacterial infections such as salmonellosis, which has considerable impacts on public health, poultry products, and economics. Many of the infections caused by *Salmonella* spp. are drug-resistant to commonly used antibiotics. One of the main reasons is the irrational use of antibiotics in both the human and animal sectors. The use of NPs has had a great impact in treating these infections. Gold, Silver, Zinc Oxide, Copper, MgO, and Selenium NPs have shown a key role in antibacterial activity against salmonellosis. The research is being done to manage their dosages and usages. However, there is a need to more widely apply the use of nanoparticles against salmonellosis in the poultry farming industry. This chapter highlights the importance of the antibacterial use of nanoparticles along with their mechanisms.

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INTRODUCTION

With continued advancement in the poultry sector, the demand for poultry products along with its socioeconomic perspective is making a huge contribution to the food animals producing industry. The world production of fresh or chilled chicken meat increased from 120.4 million to 123.6 million tonnes from the year 2021 to 2022. The United States of America, Mainland China, and Brazil are the top three chicken meat producers. The amount of eggs produced worldwide has surged by 150 percent in the last thirty years. Asia has seen the greatest of this expansion, with production nearly tripling there (FAOSTAT, 2022). Genetic Selection has played a key role in maximizing the production of poultry meat and eggs over time (Korver, et al., 2023). Poultry meat is a rich source of protein content and amino acid balance, energy, and micronutrients while eggs contain large amounts of amino acids along with essential fatty acids and high levels of vitamins (Bohrer et al., 2017). Meanwhile, viruses, fungi, and bacteria are responsible for causing various disease outbreaks in poultry (Saif et al., 2009). For example, non-typhoidal salmonella serotypes are associated with salmonellosis in poultry. Salmonellosis has a zoonotic potential which can be due to consumption of contaminated eggs and meat. There are various routes of transmission of salmonella in poultry such as contact with carrier animals like rodents, cats, and insects. Contaminated water, litter, feed, and aerosol transmission are also involved in its transmission (Shaji et al., 2023). Meanwhile, the economic losses attributed due to salmonellosis in the United States as a foodborne disease is estimated to be 4 billion dollars. (Scharff et al., 2012)

Chemical Control of Salmonellosis in Poultry

Broad-spectrum antibiotics are recommended against salmonella infections in poultry. Chloramphenicol, Neomycin Polymyxin B, Nitrofurazone, Amoxicillin, and Tetracycline, are the drugs of choice for the treatment of salmonellosis (Tariq et al., 2022). A review study published in 2020 shows that 70.0% of the studied strains of Poultry Salmonella are sensitive to drugs of the Fluoroquinolone group (nalidixic acid, norfloxacin, ciprofloxacin, enrofloxacin) and 66.67% to the cephalosporins (ceftazidime). 83.33% of strains were resistant to tetracycline drugs (tetracycline); 63.33% - β - lactams (ampicillin); 56.67% - aminoglycosides (gentamicin, kanamycin, streptomycin); 46.67% - sulfonamides (trimethoprim). Enrofloxacin is also used to treat salmonella in poultry. The recommended dose is 10 mg/kg of body weight per day for 5 to 10 days, added to the drinking water (Lenchenko et al., 2020).

Alternate Control Measures for the Control of Salmonellosis in Poultry

Essential oils have been found to act as environmental disinfectants along with decreasing intestinal colonization in chickens (Ebani et al., 2019). The dietary supplementation of essential oils (Khan et al., 2023) and organic acids is also helpful in reducing the salmonella load in the liver, spleen, and cecum (Hu et al., 2023). Probiotic supplementation of the feed leads to increased anti-salmonella IgA which helps boost humoral immunity against the salmonella infections in the birds (Shanmugasundaram et al, 2020). There is also a role of prebiotics such as non-digestible oligosaccharides and polysaccharides against salmonella which help the gut to lower the pH (Bogusławska-Tryk et al., 2012). While providing broiler birds with whole yeast cell prebiotic supplementation increases the proportion of Tregs and enhances the expression of the anti-inflammatory cytokine IL-10. All of these effects are known to modulate the immune response (Shanmugasundaram et al., 2012). Moreover, mineral nanoparticles have a role in reducing intestinal mineral antagonism thereby improving feed efficiency and immunity (Gopi et al., 2017).

Introduction of Nanoparticles

Nanoparticles (NPs) are a wide class of materials that include particulate substances, which have dimensions less than 100 nm at least. Depending on the overall shape these materials can be zero, one, two, or three-dimensional, i.e.; 0D, 1D, 2D, or 3D. Nanoparticles have a size range from 1 to 100 nm with a large surface area (Khan et al., 2023). They are extensively used in modern-day medicine for their unique ability to deliver the drugs in the optimum concentration resulting in improved patient care. Nanoparticles have also been used in diagnostic imaging technology and the development of the immunoassay. The main aspects of nanoparticles usage in medicine are their antimicrobial properties and the treatment of cancer (Maria et al., 2023). There are various classifications of the nanoparticles such as Carbon-based, Metal, Ceramic, Lipid-based, and Semiconductor NPs (Khan et al., 2019). In addition, there are two approaches for the preparation of the nanoparticles such as Bottom-Up Syntheses and Top-Down Syntheses (Wang and Xia, 2004).

Top-Down Syntheses of Nanoparticles Includes the following Steps;

- Mechanical milling
- Chemical etching
- Sputtering
- Laser Ablation
- Electro explosion

Bottom-up Synthesis of Nanoparticles is Summarized into the following steps;

- Spinning
- Template support synthesis
- Plasma or flame spraying synthesis
- Laser pyrolysis
- Chemical Vapor Deposition (CVD)
- Atomic or molecular condensation (Ibrahim et al., 2019)

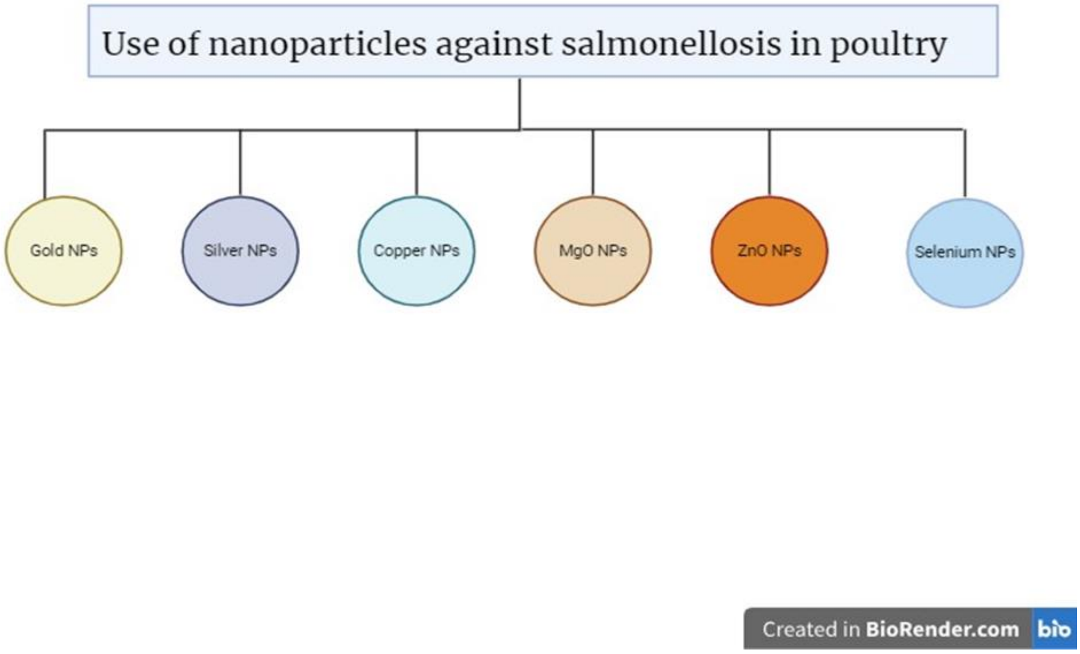

Fig. 1: Nanoparticles against Salmonella in poultry

Mechanism of Antibacterial Action of Nanoparticles

Nanoparticles (NPs) must come into contact with bacterial cells to exert their antibacterial effects. Various mechanisms can result in this contact like electrostatic attraction, receptor-ligand binding, van der Waals forces, and hydrophobic interactions. After the establishment of this contact, NPs can cross the bacterial cell membrane and accumulate along the cell's metabolic pathways and it influences the cell membrane's shape and function. This forms interaction with essential cellular components including DNA, ribosomes, lysosomes, and enzymes which results in oxidative stress, changes in membrane permeability, cellular damage, enzyme inhibition, disruption in electrolyte balance, alteration in gene expression, and protein inactivation. The antimicrobial mechanism of action of NPs is generally owes to one of the three models; metal ion release, oxidative stress induction, or non-oxidative mechanisms. Simultaneous occurrence of these three mechanisms can also be seen (Wang et al., 2017).

Table 1: Antibacterial Mechanism of Action of Some Nanoparticles

Types	Antibacterial Mechanism	References
Gold NPs	Oxidative stress due to the production of reactive free oxygen and penetration inside the cell	(Kaur et al., 2023)
Zinc Oxide NPs	Destruction of cell integrity, ROS formation, release of antimicrobial ions, mainly Zn2+ ions	(Li et al., 2011)
Silver NPs	Interferes with cell membrane and electron transport, Ag NPs work as catalysts in pollution treatment along with treatment for burns	(Li et al., 2008; Wang et al., 2017)
Titanium Oxide NPs	Releases reactive oxygen species (ROS) and damages cell membranes	(Bozdek et al., 2022)
Nitric Oxide-Releasing NPs	Produces an array of antimicrobial effector molecules acting on different targets within the microbial cell with the release of NO and reactive oxygen species	(Weller et al., 2009)

Mechanism of Nanoparticles against Salmonellosis

Nanoparticles have shown a key role against salmonellosis in poultry and the potential NPs against salmonella are discussed as follows. The biogenic silver NPs have a key role against Salmonella bacteria producing the inner membrane disruption followed by membrane dysfunction. AgNPs affect the inner membrane of bacteria without damage to the outer membrane. Moreover, the formation of antibiotic-induced reactive oxygen species (ROS) and changes in the calcium gradient also contribute to bacterial cell death (Minju et al., 2017). The antibacterial effect of Ag NPs is more pronounced at low concentrations and a study shows that Ag NPs inhibited 60–90% of *Salmonella* pathogens (Lilit G, et al., 2020). AgNPs synergized with H_2O_2 showed broad-spectrum bactericidal activity toward multi-drug-resistant *S. typhimurium* which was isolated from dairy and beef cattle (El-Gohary et al., 2020). Another study indicated that AgNPs have exhibited antimicrobial and antibiofilm activity against *S. Enteritidis.* The bacterial count decreases after using AgNPs on the biofilm as compared to the use of the sanitizer (Dias de Emery et al., 2023).

Foodborne S*almonella* pathogens are susceptible to the antibacterial activity of MgO NPs. When NPs contact bacterial cells, this interaction causes induction of oxidative stress, cell membrane leakage, and ultimately death of the cell (Yiping et al., 2016). MgO NPs gain entry within the bacterial cells by cell membrane disruption which allows them to penetrate the cytoplasm. Once these NPs enter the cytoplasm, they can either directly damage the DNA and the enzymes, or generate the reactive oxygen species (ROS) through a light-driven catalytic process. This production of ROS on the nanoparticle surface, triggered by light, results in the induction of oxidative stress in the microbial cells and leads to the death of the cell. It causes denaturation of the proteins and causes damage to the mitochondria. Additionally, interference with cellular memory is seen and trans-tolerant electron transport is also impeded. Consequently, the inflicted damage leads to the destruction of bacterial cells, prompting the release of their organelles and eventually leading to cell death (Gatou et al., 2024).

AuNPs act as an excellent biocide to eliminate *Salmonella typhi* colonies at times as short as 90 minutes (Lima et al., 2013). AuNPs obtained from *S. plagiophyllum* extract have been found to show effective antibacterial activity for biomedical applications (Dhas et al., 2020). Gold nanoparticles have shown antimicrobial activity against MDR *Salmonella* spp. obtained from fecal samples of the ruminants suffering from mastitis, respiratory signs, and diarrhea (Abdalhamed et al., 2021). The combination therapy including an antibiotic such as cefixime and a variety of NPs including Silver, Zinc oxide, Copper, and Nickel has shown antimicrobial activity against *Salmonella* Infections (Kapadia et al., 2021).

Scientific evidence demonstrated the potential of ZnO NPs as an alternative to conventional antibiotics in livestock farming (Yausheva et al., 2018). The effects of exposure to ZnO nanoparticles on the gut microbiota have been researched in various animal models (Zhu et al., 2023). Zinc Oxide NPs enhance the production of the reactive oxygen species which leads to abnormal metabolism in food pathogens including *Salmonella*. It has also been found that the exposed cells with ZnO NPs produce a high level of malondialdehyde disintegrating the bacterial cell membrane. It would also allow the ZnO NPs to enter into the cytosol to interact with cytoplasmic proteins and enzymes, producing more reactive oxygen and leading to protein aggregation and enzyme inhibition. (Krishnamoorthy et al., 2022).

The biosynthesized Selenium NPs have also demonstrated an antibacterial potential against *Salmonella typhimurium* both in vitro and in vivo experiments (Saleh et al., 2023). Selenium NPs improve the growth performance, feed conversion ratio, and meat production through their antimicrobial activity and stimulating the thyroid glands to produce the thyroid hormones in poultry. It also improves the intestinal membrane integrity and enhances the production of beneficial intestinal bacteria. Supplementation of the Selenium NPs in the laying hen's diet improves the egg production and the egg-laying capacity of the hens (Ahmad et al., 2022).

With the size of 2-350nm and increased uptake from the GIT, the Copper NPs have inhibited the growth of *Salmonella choleraesuis.* (Scott et al, 2018). However, it is reported that CuO NPs require higher concentrations to show an antimicrobial effect against *Salmonella* as tested by MIC (Duffy et al., 2018). A recent study shows that CuO NPs synthesized via the green route by using *Cassia fistula* revealed that the peace antibacterial activity was demonstrated at 280nm through UV spectrometry against *S. typhimurium*. It produces the ROS by following the type II mechanism for the production of reactive oxygen species (Rahim et al., 2024)

Conclusion

The use of nanoparticles is increasing day by day due to the wide range of their applications in diagnosis and therapeutic areas. The discussions in our book chapter include the antibacterial action of nanoparticles against salmonellosis. These nanoparticles have potential advantages against enteric pathogens and advanced research must be done to determine the applications of nanoparticles against salmonellosis on an industrial level in poultry. Salmonellosis plays a key role in mortality and morbidity in the poultry sector all over the world. There is a need to undergo further research to understand the potential application of NPs to get adopted in poultry.

REFERENCES

Abdalhamed, A. M., Ghazy, A. A., Ibrahim, E. S., Arafa, A. A., and Zeedan, G. S. (2021). Therapeutic effect of biosynthetic gold nanoparticles on multidrug-resistant Escherichia coli and Salmonella species isolated from ruminants. *Veterinary World*, *14*(12), 3200.doi: 10.14202/vetworld.2021.3200-3210

Ahmad, I., Mashwani, Z. U. R., Raja, N. I., Kazmi, A., Wahab, A., Ali, A., and Rahimi, M. (2022). Comprehensive approaches of nanoparticles for growth performance and health benefits in poultry: An update on the current scenario. *BioMed Research International*, *2022*(1), 9539908. doi: 10.1155/2022/9539908.

Bodzek, M. (2022). Nanoparticles for water disinfection by photocatalysis: A review. *Archives of Environmental Protection*, *48*(1), 3-17.

Bogusławska-Tryk, M., Piotrowska, A., and Burlikowska, K. (2012). Dietary fructans and their potential beneficial influence on health and performance parametrs in broiler chickens. *Journal of Central European Agriculture*, *13*(2), 0-0.

Bohrer, B. M. (2017). Nutrient density and nutritional value of meat products and non-meat foods high in protein. *Trends in Food Science and Technology*, *65*, 103-112.

de Emery, B. D., Chitolina, G. Z., Qadir, M. I., Furian, T. Q., Borges, K. A., de Souza Moraes, H. L., and do Nascimento, V. P. (2023). Antimicrobial and antibiofilm activity of silver nanoparticles against Salmonella Enteritidis. *Brazilian Journal of Microbiology*, *54*(1), 285. https://doi.org/10.1007/s42770-022-00868-1

Dhas, T. S., Sowmiya, P., Kumar, V. G., Ravi, M., Suthindhiran, K., Borgio, J. F., and Kumar, C. V. (2020). Antimicrobial effect of

Sargassum plagiophyllum mediated gold nanoparticles on Escherichia coli and Salmonella typhi. *Biocatalysis and Agricultural Biotechnology*, *26*, 101627.https://doi.org/10.1016/j.bcab.2020.101627

Duffy, L. L., Osmond-McLeod, M. J., Judy, J., and King, T. (2018). Investigation into the antibacterial activity of silver, zinc oxide and copper oxide nanoparticles against poultry-relevant isolates of Salmonella and Campylobacter. *Food Control*, *92*, 293-300. https://doi.org/10.1016/j.foodcont.2018.05.008

Ebani, V. V., Nardoni, S., Bertelloni, F., Tosi, G., Massi, P., Pistelli, L., and Mancianti, F. (2019). In vitro antimicrobial activity of essential oils against Salmonella enterica serotypes Enteritidis and Typhimurium strains isolated from poultry. *Molecules*, *24*(5), 900. https://doi.org/10.3390/molecules2405090

El-Gohary, F. A., Abdel-Hafez, L. J. M., Zakaria, A. I., Shata, R. R., Tahoun, A., El-Mleeh, A., and Elmahallawy, E. K. (2020). Enhanced antibacterial activity of silver nanoparticles combined with hydrogen peroxide against multidrug-resistant pathogens isolated from dairy farms and beef slaughterhouses in Egypt. *Infection and Drug Resistance*, 3485-3499. https://doi.org/10.2147/IDR.S271261

Gabrielyan, L., Badalyan, H., Gevorgyan, V., and Trchounian, A. (2020). Comparable antibacterial effects and action mechanisms of silver and iron oxide nanoparticles on Escherichia coli and Salmonella typhimurium. *Scientific Reports*, *10*(1), 13145. https://doi.org/10.1038/s41598-020-70211-x

Gatou, M. A., Skylla, E., Dourou, P., Pippa, N., Gazouli, M., Lagopati, N., and Pavlatou, E. A. (2024). Magnesium Oxide (MgO) Nanoparticles: Synthetic Strategies and Biomedical Applications. *Crystals*, *14*(3), 215. https://doi.org/10.3390/cryst14030215

He, Y., Ingudam, S., Reed, S., Gehring, A., Strobaugh, T. P., and Irwin, P. (2016). Study on the mechanism of antibacterial action of magnesium oxide nanoparticles against foodborne pathogens. *Journal of Nanobiotechnology*, *14*, 1-9. https://doi.org/10.1186/s12951-016-0202-0

Hu, Z., Liu, L., Guo, F., Huang, J., Qiao, J., Bi, R., and Wang, Z. (2023). Dietary supplemental coated essential oils and organic acids mixture improves growth performance and gut health along with reduces Salmonella load of broiler chickens infected with Salmonella Enteritidis. *Journal of Animal Science and Biotechnology*, *14*(1), 95. https://doi.org/10.1186/s40104-023-00889-2

Kapadia, C., Alhazmi, A., Patel, N., Elesawy, B. H., Sayyed, R. Z., Lokhandwala, F., and Datta, R. (2021). Nanoparticles combined with cefixime as an effective synergistic strategy against Salmonella enterica typhi. *Saudi Journal of Biological Sciences*, *28*(8), 4164-4172. https://doi.org/10.1016/j.sjbs.2021.05.032

Kaur, H., Rauwel, P., and Rauwel, E. (2023). Antimicrobial nanoparticles: synthesis, mechanism of actions. In *Antimicrobial activity of nanoparticles* (pp. 155-202). *Elsevier*. https://doi.org/10.1016/B978-0-12-821637-8.00008-0.

Kausar, M., Saleem, Z., Azhar, R., Rukhsar, G., Ali, M., Fan, C., and Khan, A. M. A. Role Of Nanoparticles In Covid-19 Management. https://Doi.Org/10.61748/Cam.2023/010

Khan, A. M. A., Arshad, M. A., Naeem, R. F., Shafiq, M. S., Irshad, M., Shahid, D. A., and Usmani, M. W. Role Of Essential Oils And Other Alternatives To Control Ticks (Hyalomma Species) The Major Cause Of Cchf (a Threat For Humans And Livestock). https://Doi.Org/10.61748/Cam.2023/006

Khan, A. M. A., Wei, C. R., Fatima, K., Ali, A., Akram, M. S., Saeed, Z., and Ullah, H. Use Of Nanoparticles As Antioxidant Agents To Combat Bacterial Infections And Its Benefits To Intestinal Microbiota And Immune Response. https://Doi.Org/10.61748/Cam.2023/001

Khan, I., Saeed, K., and Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, *12*(7), 908-931. https://doi.org/10.1016/j.arabjc.2017.05.011 .

Korver, D. R. (2023). Current challenges in poultry nutrition, health, and welfare. *Animal*, *17*, 100755.

Krishnamoorthy, R., Athinarayanan, J., Periyasamy, V. S., Alshuniaber, M. A., Alshammari, G., Hakeem, M. J., and Alshatwi, A. A. (2022). Antibacterial mechanisms of zinc oxide nanoparticle against bacterial food pathogens resistant to beta-lactam antibiotics. *Molecules*, *27*(8), 2489. https://doi.org/10.3390/molecules27082489

Lenchenko, E., Blumenkrants, D., Vatnikov, Y., Kulikov, E., Khai, V., Sachivkina, N., and Mansur, T. (2020). Poultry Salmonella Sensitivity to Antibiotics. *Systematic Reviews in Pharmacy*, *11*(2).

Li, M., Zhu, L., and Lin, D. (2011). Toxicity of ZnO nanoparticles to Escherichia coli: mechanism and the influence of medium components. *Environmental Science and Technology*, *45*(5), 1977-1983. doi: 10.1021/es102624t

Li, Q., Mahendra, S., Lyon, D. Y., Brunet, L., Liga, M. V., Li, D., and Alvarez, P. J. (2008). Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. *Water Research*, *42*(18), 4591-4602.doi:10.1016/j.watres.2008.08.015

Lima, E., Guerra, R., Lara, V., and Guzmán, A. (2013). Gold nanoparticles as efficient antimicrobial agents for Escherichia coli and Salmonella typhi. *Chemistry Central Journal*, *7*, 1-7. https://doi.org/10.1186/1752-153X-7-11

Marappan Gopi, M. G., Beulah Pearlin, B. P., Kumar, R. D., Muthuvel Shanmathy, M. S., & Govindasamy Prabakar, G. P. (2017). Role of nanoparticles in animal and poultry nutrition: modes of action and applications in formulating feed additives and food processing.

Rahim, M., Khan, M., Abbas, N., Khalid, M., and Hussain, M. A. (2024). Synthesis, characterization, and antimicrobial activity of Cassia fistula mediated Cobalt doped Copper oxide nanoparticle against Salmonella typhi a step toward antibacterial nanomedicine. *International Journal of Nanoelectronics and Materials (IJNeaM)*, *17*(1), 147-152. https://doi.org/10.58915/ijneam.v17i1.504

Randall, L. P., Cooles, S. W., Coldham, N. C., Stapleton, K. S., Piddock, L. J., and Woodward, M. J. (2006). Modification of enrofloxacin treatment regimens for poultry experimentally infected with Salmonella enterica serovar Typhimurium DT104 to minimize selection of resistance. *Antimicrobial agents and chemotherapy*, *50*(12), 4030-4037..https://doi.org/10.1128/aac.00525-06

Saif, Y. M. (2009). *Diseases of poultry*. John Wiley and Sons.

Saleh, A., El-Masry, T. A., Negm, W. A., Alotaibi, B., Elharty, M. E., Alotaibi, K. N., and Elekhnawy, E. (2023). Unravelling the antibacterial potential of biosynthesized selenium nanoparticles against Salmonella Typhimurium food pathogen: in vitro and in vivo investigation. *European Review for Medical and Pharmacological Sciences*, *27*(8).

Scharff, R. L. (2012). Economic burden from health losses due to foodborne illness in the United States. *Journal of Food Protection*, *75*(1), 123-131.

Scott, A., Vadalasetty, K. P., Chwalibog, A., and Sawosz, E. (2018). Copper nanoparticles as an alternative feed additive in poultry diet: a review. *Nanotechnology Reviews*, *7*(1), 69-93.. https://doi.org/10.1515/ntrev-2017-0159

Seong, M., and Lee, D. G. (2017). Silver nanoparticles against Salmonella enterica serotype typhimurium: role of inner membrane dysfunction. *Current Microbiology*, *74*, 661-670. https://doi.org/10.1007/s00284-017-1235-9

Shaji, S., Selvaraj, R. K., and Shanmugasundaram, R. (2023). Salmonella infection in poultry: a review on the pathogen and control strategies. *Microorganisms*, *11*(11), 2814. https://doi.org/10.3390/microorganisms1111281

Shanmugasundaram, R., and Selvaraj, R. K. (2012). Effect of killed whole yeast cell prebiotic supplementation on broiler performance and intestinal immune cell parameters. *Poultry Science*, *91*(1), 107-111. https://doi.org/10.3382/ps.2011-01732.

Shanmugasundaram, R., Applegate, T. J., and Selvaraj, R. K. (2020). Effect of Bacillus subtilis and Bacillus licheniformis probiotic supplementation on cecal Salmonella load in broilers challenged with salmonella. *Journal of Applied Poultry Research*, *29*(4), 808-816.https://doi.org/10.1016/j.japr.2020.07.003

Tariq, S., Samad, A., Hamza, M., Ahmer, A., Muazzam, A., Ahmad, S., and Amhabj, A. M. A. (2022). Salmonella in poultry; an overview. *International Journal of Multidisciplinary Sciences and Arts*, *1*(1), 80-84.

Van Alfen, N. K. (2014). *Encyclopedia of agriculture and food systems*. Elsevier.

Wang, L., Hu, C., and Shao, L. (2017). The antimicrobial activity of nanoparticles: present situation and prospects for the future. *International Journal of Nanomedicine*, 1227-1249. https://doi.org/10.2147/IJN.S121956

Wang, Y., and Xia, Y. (2004). Bottom-up and top-down approaches to the synthesis of monodispersed spherical colloids of low melting-point metals. *Nano Letters*, *4*(10), 2047-2050.

Weller, R. B. (2009). Nitric oxide–containing nanoparticles as an antimicrobial agent and enhancer of wound healing. *Journal of Investigative Dermatology*, *129*(10), 2335-2337.https://doi.org/10.1038/jid.2009.149.

Yausheva, E., Miroshnikov, S., and Sizova, E. (2018). Intestinal microbiome of broiler chickens after use of nanoparticles and metal salts. *Environmental Science and Pollution Research*, *25*(18), 18109-18120.

Zhu, L., Luo, M., Zhang, Y., Fang, F., Li, M., An, F., and Zhang, J. (2023). Free radical as a double-edged sword in disease: Deriving strategic opportunities for nanotherapeutics. *Coordination Chemistry Reviews*, *475*, 214875.