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Synthesis Of Green Nanoparticles Using Bioactive Compounds From Plants To Enhance Fish Shelf Life: A Sustainable Approach Inspired By Fishermen

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Abstract:

Fish is protein rich food that needs skilful handling (Sujatha et al,2013). Main reason behind this is fish spoilage after capture due to high tropical heat which enhances activities of bacteria, enzyme and chemical oxidation of fat in fish. Due to improper handling near about 20-35% of fish harvest are wasted in India. These major losses could be minimized by application of skilful handling, processing and preservation techniques. The utilization of plant extract as reducing and stabilizing agents for nanoparticle synthesis offers numerous advantages over traditional chemical method including cost effectiveness, scalability and absence of toxic contaminant thus making plant mediated synthesis a sustainable alternative to its counterparts. (Singh et al,2023). Green synthesis uses plant extract rich in bioactive compound like flavonoids, alkaloid and phenolics as natural reducing and stabilizing agents instead of conventional method using harmful reducing agents. Green synthesis adheres to biodegradability, energy efficiency, waste reduction and uses of renewable resources as plants. (Abuzeid et al,2023). Use of indigenous plant knowledge for bioactive extraction connect modern nanotechnology with ancient ecological wisdom.

Keywords:

1.Deterioration

2. Whatman

3. crystallinity

4. minced

5. capping

1. INTRODUCTION:

Fish spoilage is a major concern in seafood industry due to its rapid deterioration which affects quality, safety and shelf life. Due to high moisture content and nutrient rich environment microbial growth occur which leads to off-odours, slime formation and texture degradation. (Siddiqui et al,2024). Flavour, texture and colour change due to activity of autolytic enzyme in fish tissue which breakdown protein and lipids. Due to lipid oxidation, rancidity occur which reduces nutritional value. Due to temperature fluctuation, storage and transportation face challenges. Using natural resources, we switch towards greener, safer, more efficient food technologies and environmental conservation. There is urgent need to reduce pollution and ecological foot print of industrial activities. Green synthesis aligns with traditional fish preservation technique by using natural properties of plant to create nanoparticle that can be used to extend shelf life of fish without synthetic preservatives. (Nie et al,2025). Use of plant-based nanoparticle offer natural ways to inhibit microbial growth which is essential in region with limited refrigeration. Bioactive plant compound possess antioxidant, antimicrobial and anti-inflammatory properties which is alternative to chemical preservative. Bacteria like Pseudomonas, Lactobacillus species are crucial contributor to fish spoilage (karanth et al,2023). Due to their activity volatile compound like cadaverine produce which cause unpleasant odour. Breakdown of protein produce ammonia which causes off odours. Refrigeration is essential as these bacteria grow rapidly at 5 C to 20 C. Nanoparticle particularly Silver, Zinc oxide, copper-based nanoparticle possesses antibacterial effects. Nanoparticle like chitosan and copper oxide exhibit antifungal properties. Nanoparticle made from plant extract can be added to food products to reduce oxidation which directly maintain color, flavour and nutritional value of food. Plant derived bioactive compound like terpenoids, alkaloids and flavonoids eliminate microbial growth. Rosemary extract rich in antioxidant and antimicrobial compound contains rosmarinic acid which is used in nanoparticle synthesis for fish preservation. (Aziz et al,2022). Plants like green tea, coffee, Poplar etc. possess polyphenol, flavonoids and alkaloid which have antioxidant, antimicrobial properties. (Othman et al,2019). Plants essential oil from thyme, rosemary, clove shows effective result against bacteria and fungi in seafood. Silver nanoparticles were mainly used to control disease due to their bactericide capacity. (Gong et al,2007). In aquaculture, one major concern was infectious disease control caused by bacteria, virus, fungus and parasites. Excessive application of traditional antimicrobial compounds provoked resistant strains making treatment failure. (Pelgrift et al,2013). Some researchers studied silver nanoparticle effect for diverse ways to control pathogens from fishes. (Swain et al,2014). It was reported (Barkat et al, 2016. Daniel et al,2016) that antiparasitic and antifungal effect of AgNPs encapsulated with starch and applied through immersion baths (20 minutes) with 10 ng of nanoparticle concentration in Carassius auratus,infected with Icthyophthirius multifilis and Aphanomyces invadans.The results showed that fishes recover after three days without toxic effect to AgNPs application. Recently it was development research about to vaccines generation to protect Asiatic carp using nanoparticles against Listonella anguillarum bacteria. (Kumar et al,2008). Due to nanoparticles unique property like bioavailability nanoparticle like silver,chitosan can effectively reduce oxidative stress in fish. (Aly et al,2023). Important target of food industry is to extend product shelf life in order to preserve not only freshness but also food quality. Nanoparticles can be used to slow down decay in quality thus keeping color and flavor of product. (Chellaram et al,2014). Green methods of nanoparticle synthesis have several advantages over traditional chemical method. Green synthesis aims to protect environment by substituting harmful chemicals. As such yeast, fungi, bacteria, algae and plant extract are favoured as reducing agents over toxic chemicals for preparation of metal and metal oxide nanoparticles. (Abuzeid et al,2023). Plant components including leaves, fruits, roots, stems and seeds have been widely utilized to synthesize different nanoparticles. (Hano et al,2021). For green synthesis of silver nanoparticles a silver metal ion solution and reducing biological agent required. The easiest and least expensive method of producing AgNPs is to reduce and stabilize Ag ions using mixture of biomolecules such as polysaccharides, alkaloid, terpenes. (Dhaka et al,2023). One of main challenges facing green extraction is need to balance sustainability and efficiency. (Chemat et al,2012). United States based safety evaluation agencies such as FDA and EPA including Directorate of European Health and Consumer protection and many other regulatory authorities have released several guidelines on potential human risk associated with use of nanostructure materials in food. (He et al, 2016). Polymeric nanoparticle is suitable for encapsulation of bioactive compound such as flavonoids and for the release of these compounds in an acidic environment such as in stomach. (Pool et al,2012). Encapsulated forms of ingredients exhibit numerous advantages including consecutive delivery of multiple active ingredients, shelf-life extension, increased stability and Ph triggered controlled release. (Momin et al,2013). Green nanotechnology concept aims to reduce environmental impact of nanotechnology while seeking to maximize its societal benefit. (Jafarzadeh et al,2024).

2. Methodology:

Materials and Plant Extract Preparation

Fresh plant material (e.g., leaves, stems, or roots of selected medicinal/traditional plants known for bioactive compounds) will be collected, washed thoroughly with deionised water, and shade-dried until constant weight. The dried material will then be ground into a fine powder using a laboratory mill. An aqueous extract will be prepared by mixing a defined amount of plant powder (e.g., 20 g) with a measured volume of distilled water (e.g., 200 mL) and heating at 60–80 °C for 30–60 minutes under continuous stirring. After cooling, the extract will be filtered through Whatman No. 1 filter paper and stored at 4 °C until use.

Green Nanoparticle Synthesis

The aqueous plant extract will act as both reducing and capping agent in the green synthesis of metal or metal-oxide nanoparticles. A precursor salt solution (e.g., metal nitrate or acetate) will be prepared at a given molarity (e.g., 0.01 M). Under continuous stirring, the plant extract will be gradually added to the precursor solution in a volume ratio (e.g., 1:1) and the mixture will be maintained at ambient or elevated temperature (e.g., 50–90 °C) for a fixed time (e.g., 1-2 h). The reaction progress will be monitored by observing colour change and by using UV-Vis spectrophotometry for characteristic plasmon resonance peaks. The resultant colloidal suspension will be centrifuged at ~10,000 rpm for 10 minutes, the pellet collected, washed repeatedly with deionised water and ethanol to remove unreacted material, and then dried in an oven at ~60 °C to obtain dry nanoparticle powder. In some cases, calcination at e.g., 300 °C for 2 hours may be used to improve crystallinity (e.g., as in Mahato et al., 2024).

Characterisation of Nanoparticles

The synthesized nanoparticles will be characterised using a suite of techniques:

- **UV-visible spectrophotometry** to detect the surface plasmon resonance peak and confirm nanoparticle formation.
- **X-ray diffraction (XRD)** to determine crystalline phase and average crystallite size via Scherrer equation.
- **Fourier transform infrared spectroscopy (FTIR)** to identify surface functional groups (originating from plant phytochemicals) that may act as capping agents.
- **Transmission electron microscopy (TEM) or scanning electron microscopy (SEM)** to visualise particle morphology and size distribution.
- **Dynamic light scattering (DLS)** and zeta potential analysis to assess hydrodynamic particle size and colloidal stability.
- **Thermogravimetric analysis (TGA)** if needed to assess thermal stability of the nanoparticles.

These steps ensure comprehensive characterisation of morphology, size, crystallinity, and surface chemistry, critical for linking nanoparticle properties to antimicrobial or antioxidant function (Frontiers study).

Incorporation into Fish Preservation System

Once characterised, the green-synthesised nanoparticles will be incorporated into a fish preservation system inspired by fishermen practices for example by coating or immersing freshly harvested fish fillets (or minced fish) in nanoparticle-infused preservative solution or packaging film.

- **Sample preparation**: Fresh fish (e.g., fillets of a selected species) will be cleaned, filleted under hygienic conditions, and randomly assigned into treatment groups (control, plant-extract only, nanoparticle only, nanoparticle plant extract).
- **Application**: The nanoparticles will be applied at a defined dose (e.g., mg NP/kg fish or mg NP per m^2 in a coating) based on preliminary optimisation. The fish will be dipped or sprayed and then packaged in air-tight film and stored at refrigeration temperature (e.g., 4 ± 1 °C) for a predetermined storage period (e.g., 0, 3, 6, 9 days).
- **Monitoring**: At each time point, samples will be analysed for sensory attributes (odour, colour, texture), physicochemical parameters (pH, total volatile base nitrogen (TVB-N), thiobarbituric acid reactive substances (TBARS) for lipid oxidation), and microbiological counts (total viable count, coliforms, spoilage bacteria). These parameters are commonly used to evaluate shelf-life extension in fish. For example, Mahato et al. (2024) used pH, TVB-N, TBARS and microbial loads for minced fish treated with ZnO nanoparticles.
- **Role of Plant Bioactive Compounds and Sustainable Approach**

The innovation lies in harnessing plant-derived bioactive compounds (such as phenolics, flavonoids, terpenoids, etc.) which act as reducing and stabilising agents during nanoparticle formation, and concurrently provide antimicrobial and antioxidant benefits to the resulting system. The co-action of the nanoparticle's high surface area and the capping phytochemicals creates a synergistic environment for inhibiting microbial growth and oxidative spoilage in fish. This approach aligns with the sustainable, eco-friendly aspirations of small-scale fishermen: by using locally available plant extracts and minimal chemical reagents, waste and energy consumption are reduced while adding value to post-harvest fish. The methodology thereby integrates nano-biotechnology with traditional fish handling practices, promoting shelf-life extension and reducing post-harvest losses (Shakeel et al., 2025).

Data Analysis

All experimental treatments will be performed in triplicate and storage studies repeated at least twice to ensure statistical reliability. Data will be expressed as mean ± standard deviation. Statistical analysis will be conducted using ANOVA followed by post hoc tests (e.g., Tukey's HSD) to detect significant differences among treatments ($p < 0.05$). Shelf-life extension will be evaluated by comparing key spoilage indicators (e.g., TVB-N threshold, microbial counts) across treatments and storage days. Correlations between nanoparticle characterisation parameters (size, zeta potential, phytochemical content) and preservation efficacy will also be explored through regression analyses. (Frontiers.,2022)

Safety, Environmental and Fishermen-Centric Considerations

Given the origin of nanoparticles, it is essential to assess potential nanoparticle release into aquatic ecosystems or residual uptake in fish tissue. While the green-synthesis route tends to reduce toxic reagents, attention must be paid to nanoparticle size, dose, and possible migration/leaching. Studies in aquaculture caution about nanoparticle toxicity to aquatic organisms at certain concentrations (Blue Biotechnology review). The methodology will therefore include:

- A preliminary toxicity screen of the nanoparticles on non-target aquatic organisms (e.g., local freshwater fish species) using standard acute toxicity tests.
- Measurement of nanoparticle residuals in fish tissue post-treatment (e.g., by ICP-MS) to assess food safety implications.
- Dialogue with local fishermen to ensure that the preservation approach is compatible with their existing cold-chain or ice-based storage practices and minimal cost. Adoption of low-cost plant materials and minimal infrastructure ensures that the method remains approachable for small-scale fishermen. (Biswas, R., et al. 2023).

Conclusion:

This review demonstrates that nanotechnology holds immense potential for transforming aquaculture sector, through use of bioactive compounds from plant, shelf life of fish can be extended. Extending fish shelf life using nanoparticle containing plant derived bioactive compound offer promising future toward greater sustainability and food security in food industry. By reducing spoilage and waste, this approach can improve resource utilization and access to nutritious protein for more people contributing to both environment and social well-being.

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