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Nanoparticle-Based Delivery Systems for Herbal Compounds in Aquaculture Feeds

Haneen Mowfak Ahmed [1*], Azhar majid Ibrahim [2], Waseem Amer Hashem [3]

[1*] Department of Animal Production Techniques, Agricultural Technical College, Northern Technical University, Mosul, Iraq. Email: haneen.mowfak@ntu.edu.iq

[2] Department of Animal Production Techniques, Agricultural Technical College, Northern Technical University, Mosul, Iraq. Email: dr.azharm@ntu.edu.iq

[3] Department of Therapeutic Nutrition Techniques, Al-Nimrud Technical Institute, Northern Technical University, Mosul, Iraq. Email: wasseem_amer@ntu.edu.iq

Abstract

The use of the nanoparticle-based delivery system in aquaculture has become a prospective method to improve bioavailability, stability, and controlled release of herbal bioactive compounds. These systems, especially polymeric nanoparticles, have a great potential in surmounting the shortcomings of herbal compounds, which include low solubility and instability in aqueous conditions. The research aimed to prepare ginger extract-loaded nanoparticles with the use of PLGA (Poly (lactic-co-glycolic acid)) as the encapsulating polymer and analyze their usefulness in the controlled release in aquaculture environments. The ginger extract was acquired through the hot water extraction process, and the synthesis of the nanoparticles was done through the solvent evaporation technique. Some of the methods, such as UV-Vis Spectrophotometry and Dark Field Microscopy, were used to characterize the nanoparticles. Formulation efficiency of 85% and drug loading of 12.5% were identified to determine the effectiveness of the formulation. The release profiles of the in vitro experiment at different pH levels (1.5, 5.5, and 7.4) showed that it was pH-sensitive as it was more released at basic pH, which is a replica of the aquatic environment. Diffusion-controlled and polymer relaxation mechanisms were observed in all conditions through the release kinetics. The findings have shown that nanoparticle systems can be helpful in terms of delivering bioactive herbal compounds in a sustained and controlled fashion, which helps to improve the health, growth, and immunity of fish. To sum up, the ginger-loaded polymeric nanoparticles are a promising approach to sustainable aquaculture, which has increased bioavailability and stability of herbal compounds, yet issues with scalability and safety still need to be investigated.

*Corresponding Author: Haneen Mowfak Ahmed, E-mail: haneen.mowfak@ntu.edu.iq

Keywords

Aquaculture, controlled release, encapsulation efficiency, ginger extract, nanoparticle-based delivery systems, pH-sensitive release, PLGA.

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Introduction

The increased focus on the need for sustainable aquaculture has also resulted in the pursuit of new technologies to improve the efficacy of the feeds (Costa, 2025). The use of nanoparticle-based delivery systems to herbal compounds in aquaculture feeds is one of the possible approaches (Rao & Tiwari, 2023). Nanotechnology would be applicable in enhancing bioavailability, stability, and controlled release of bioactive compounds, including those in herbs like garlic, turmeric, and ginger. These compounds possess a wide range of uses in virtue of their antimicrobial, immunomodulatory, and growth-promoting capabilities. Nevertheless, such herb compounds have good health effects, but are insoluble and also unstable in aqueous media. This has reduced the need to use these herbal extracts in aquaculture systems, but new delivery systems have been established to improve the adoption and efficacy of these herbal extracts. The overall research hypothesis is to explore the possibility of using polymeric nanoparticles to entrap ginger extract and establish their relevance in improving the bioavailability and the controlled release of ginger bioactives, especially under different pH conditions, which simulate the aquatic digestive system. The encapsulation is typically carried out with the help of polymeric nanoparticles, namely, PLGA (Poly (lactic-co-glycolic acid)), because of its biodegradation and biocompatibility (Elmowafy et al., 2023; Yang et al., 2023). This will help in overcoming the insolubility and instability of the herbal compounds and in the successful transfer of the active compounds across the digestive system in fish and aquatic plants (Dezfooli et al., 2019; Kamble et al., 2024; Kapoor et al., 2025).

The issue studied in the paper is that conventional methods of application of herbal compounds into aquaculture are less efficient, which can result in lowered absorption rates and the absence of therapeutic impact owing to destruction during the time spent in the water habitats. The answer would be in thinking about nanoparticle-based systems, which enhance the stability and bioavailability of these compounds (Daabool, 2022). However, the problems with their scalability, cost-to-produce, and possible toxicity of nanoparticles in aquatic environments remain open and should be addressed using these systems (Kamble et al., 2024; Fajardo et al., 2022; Shah & Mraz, 2020). The research hypothesis will be as follows: Ginger extract entrapped into polymeric nanoparticles will exhibit a higher bioavailability and controlled release profile than free ginger extract. More specifically, it is presupposed that the nanoparticles would be pH-sensitive in their release behavior, which will ensure that the bioactive ginger compounds entrap the best of aquatic organisms and plants, such as water spinach (Ipomoea aquatica), that could be used as a bioremediation tool in aquaculture systems (Zehra et al., 2021; Masoomi Dezfooli et al., 2019).

The most important findings of this article include the production and characterization of polymeric nanoparticles to encapsulate ginger extract, as well as the analysis of their encapsulation characteristics, drug loading, and release kinetics under simulated gastrointestinal conditions that mimic those in aquaculture (Patel & Joshi, 2022). In the current paper, the kinetics of drug release and pH-sensitive release profiles of the nanoparticles are also analyzed, which provides an impression of how the nanoparticles can be used in sustainable aquaculture activities. The results of this research will be relevant to improving more efficient and environmentally-friendly delivery systems of herbs in fish farming.

There are several significant sections of the article: materials and methods, where the synthesis and characterization of nanoparticles will be described; results, based on which the data on encapsulation efficiency, drug loading, and in vitro release profile will be presented; discussion, which is going to interpret the findings in the context of the existing current literature on the nanoparticle-based delivery system to aquaculture (Shah et al., 2020; Maghraby et al., 2023).

In summary, this paper indicates that nanotechnology has the potential to enhance the therapeutic and nutritional efficacy of herbal compounds in aquaculture diets as a sustainable aquaculture system to reduce the use of antibiotics and increase the overall health of fish. More studies could be dedicated to the optimization of nanopart production and the use of toxicological studies to define the safety of such systems in aquaculture (Khan et al., 2024; Adilbekov et al., 2025).

Literature survey

Nanoparticle-based delivery systems have received much attention in the field of aquaculture to enhance the bioavailability, stability, and controlled release of biologically active compounds in herbs. There is no doubt that nanotechnology brings up the most effective and practical ways to enhance the therapeutic and nutritional properties of herbal components, which in turn can find wide applications through their antimicrobial, immunomodulatory, and growth-promoting attributes. According to (Samanta et al., 2022), the incorporation of nanoparticles in the manufacturing of nutraceuticals can render herbal products such as garlic and turmeric bioavailable. As a result, the lipid-based nanocarriers facilitate the fish digestive process by avoiding degradation and ensuring the release of nutrients in a controlled manner (Kumar & Yadav, 2024). In the same manner, Kamble et al. (2024) observed that organic nanoparticles with phytobiotics have the potential to deliver growth and immunity of fish through long-term and localized delivery, which improves. The antimicrobial and immunostimulatory effects of herbs, including neem, turmeric, and garlic, have also been known to increase the immunity and resistance of the fish against diseases (Khan et al., 2024). Their low solubility and stability in water hinder their effectiveness. The problems can be mitigated in nanoparticle encapsulation through enhancement of their solubility, bioavailability, and stability. Polymeric nanoparticles (like poly (lactic-co-glycolic acid) (PLGA)) can release the herbal compounds in fish feeds over a period of time in a controlled way (Dezfooli et al., 2019). Similarly, nanoparticles made of lipids (solid lipid nanoparticles, SLNs, and nanostructured lipid carriers, NLCs) can be utilized to carry herbal compounds that are hydrophobic and increase their absorption and stability in the intestine (Kamble et al., 2024; Mitra et al., 2025).

Nanoparticles have high therapeutic and growth-promotional potential in aquaculture in terms of herbal systems. The systems promote the immunity of fish, and it is unnecessary to use antibiotics and chemicals (Shah & Mraz, 2020). Dietary supplements such as nano encapsulated herbs, such as garlic and turmeric, have been found to boost immune functions, besides boosting nutritional uptakes, which translates into better growth performances. According to Fajardo et al. (2022), the nanoparticle preparations increase the effectiveness of herbal compounds, which positively influence feed conversion ratios and total fish growth, and others, which are the key factors of sustainable production of aquaculture. However, the systems utilizing nanoparticles also have certain drawbacks in terms of the questions of scalability and safety. Khan et al. (2024) argue that although the use of nanoparticles in laboratory environments proves to be promising, it is not yet ready to be used in commercial aquaculture since its manufacturing is not the most economical, and the equipment needed is not only very costly but also needs dedicated facilities. Furthermore, possible toxicity and bioaccumulation of nanoparticles in fish and aquatic systems, and the necessity to conduct a thorough toxicological assessment were also mentioned by Adilbekov et al. (2025). The use of such technologies should be well tested in terms of safety, as it needs to be ensured that they will not negatively impact the aquatic organisms or people who consume them.

The field of nanotechnology in fish farming is a new area of regulation. During the regulatory approval procedure, Onyeaka et al. (2022) mention that the safety tests should be performed on a large scale to guarantee the safety of the environment and consumers. The development of biodegradable and environmentally friendly nanomaterials is likely to overcome most of these issues, but these materials are not nontoxic and scalable (Zehra et al., 2020). With the development of such technologies and the regulation systems being enhanced, there will be an opportunity to have the nanoparticle-based delivery systems that can be applied commercially.

To sum up, nanoparticle delivery systems create opportunities in improving bioavailability, stability, and controlled delivery of herbal compounds in aquaculture feeds. They can also sustain good health, immunity, and growth of fish, and reduce the use of antibiotics, which will render the practice of aquaculture more sustainable. Despite the existing issues with the scalability of production, safety, and regulation, the current nanotechnology discoveries and the creation of safer and environmentally-friendly substances are bound to spur their further use in the aquaculture industry.

Materials and Methods

Ginger Extract

Ginger extract was obtained from Zingiber officinale rhizomes using a hot water extraction method. The ginger rhizomes were thoroughly washed, peeled, and grated into a fine paste. A 20-gram piece of ginger was taken, grated, and then mixed with distilled water, the total amount being 200mL, and boiling was done for 30 minutes. The solution was then left to cool down to room temperature so that the gingerols, shogaols, and all other soluble compounds in water could be extracted. The mixture of ginger and water was allowed to cool down and filtered either using a fine mesh or a Whatman filter paper to collect the liquid portion, leaving the solid ginger portion behind. To evaporate the water in the liquid extract, a rotary evaporator was used at 40 °C under low pressure. The ginger extracts were stored in airtight bottles that were stored at 4 °C to prevent the destruction of the active constituents (Maghraby et al., 2023).

An alcohol-free extraction of Zingiber officinale rhizomes was done, and the liquid extract was subsequently concentrated by water evaporation under reduced pressure using a rotary evaporator at 40 °C. The concentrated ginger extracts were stored in the dark in closed bottles at room temperature, or at 4 °C to prevent the deterioration of bioactive compounds (Maghraby et al., 2023).

Synthesis of Nanoparticle-Based Delivery Systems

The concentrated ginger extract was the active herb compound that got encapsulated to create the nanoparticles. The polymeric nanoparticles were formed through solvent evaporation due to their high efficiency in bioactive compounds -until this point- entrapment. The polymeric solution was prepared through the dissolution of PLGA (Poly (lactic-co-glycolic acid)) in an organic solvent like acetone, at a concentration of 2mg/ml (Begines et al., 2020).

Ginger extract was then added to the polymer solution so that it could be evenly distributed to provide homogeneity in the distribution of the active ingredients. This was mixed with a solution of PVA (Polyvinyl alcohol) in water, which was to stabilize the nanoparticles and then aggregate. Stirring or sonicating was employed in order to provide a stabilized emulsion of oil in water. This emulsion was then subjected to solvent evaporation at decreased pressure using the rotary evaporator, because it was feasible to obtain the organic solvent, and only the polymer crystallized and preserved the bioactive compounds (Kamble et al., 2024).

The nanoparticles were obtained by centrifugation of the solids once the solvent had been evaporated at 12,000 x g in 30 minutes. Two to three times washing of the nanoparticles with distilled water was then done to get rid of all the traces of solvent, unbound ginger extract, or other contaminants. To make sure that bioactive compounds in the nanoparticles were not destroyed, the recipe of the end nanoparticle was pooled in closed test tubes at 4 °C (Begines et al., 2020). Following this, it is upon this that the following nanoparticles could be further defined and used in the preparation of aquaculture feed. The general plan of the process of nanoparticle synthesis and their description is depicted in Figure 1, and comprises the chain of operations starting with the synthesis of the extract and the polymer solution, emulsification, solvent removal, purification, and storage.

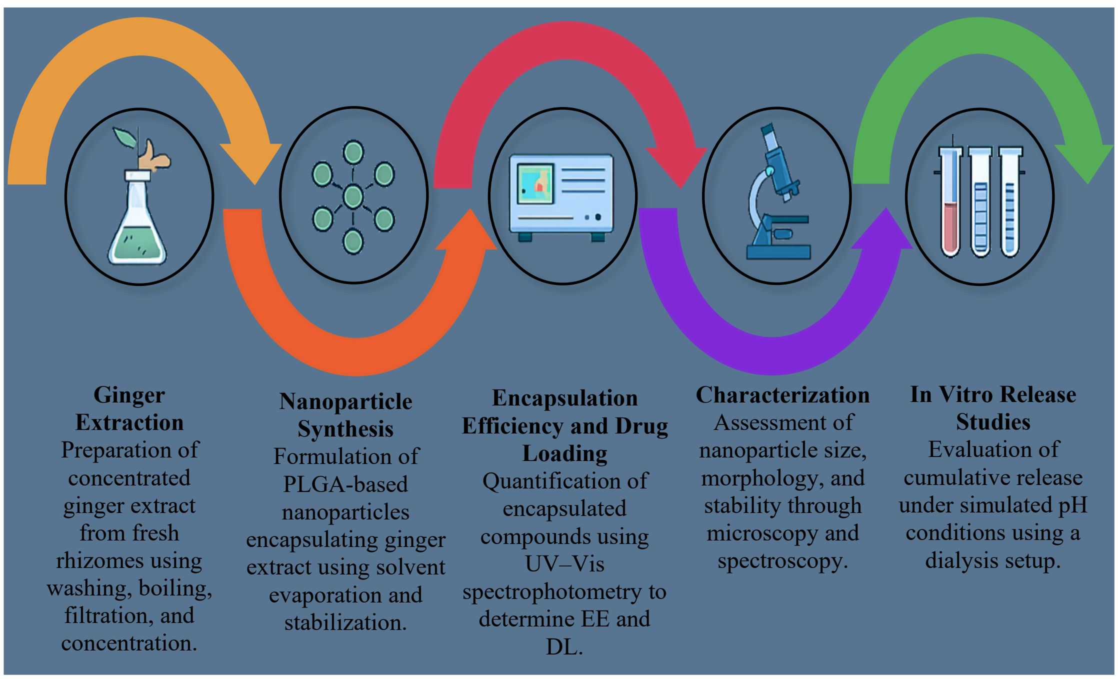

Figure 1. Flowchart illustrating the methodology for ginger extract nanoparticle formulation and characterization

Encapsulation Efficiency and Drug Loading

The Encapsulation Efficiency (EE) was obtained by UV-Vi's spectrophotometry, whereas the Drug Loading (DL) was obtained by the ultrafiltration method of the nanoparticles. The measurements will aim at determining the efficiency of the nanoparticle formulation of the herbal compounds, as well as determining the degree to which the active ingredient is successfully loaded into the nanoparticles.

Encapsulation Efficiency (EE):

This is a ratio of the total weight of the herbal compound effectively encapsulated in the nanoparticles. The isolation of unencapsulated herbal in the nanoparticle suspension, in computing EE, was performed through ultrafiltration, which is the isolation of free or unencapsulated ginger extract in the system. The concentration of the herbal compound trapped in the nanoparticles was then compared using the UV-Vis spectrophotometry at the respective wavelengths of the ginger compounds (e.g., the gingerols or shogaols).

The formula for calculating EE is as follows:

$$EE(\%)=\left(\frac{\text{Total amount of herbal compound encapsulated}}{\text{/Total amount of herbal compound used}}\right)\times 100$$

The mass of the herbal compound enclosed in the total is the measure of the active ginger extract effectively enclosed in the nanoparticles. Mass of the herbal compound used in totality is the initial mass of the ginger extract, which was added to the process of nanoparticle production.

High encapsulation efficiency is an indication that a greater percentage of the active ingredient is now being efficiently incorporated into the nanoparticle system, so that the formulation is effective in delivering the bioactive compounds.

Drug Loading (DL):

Drug loading is defined as the concentration of the herbal constituent in the nanoparticles as compared to the total mass of the nanoparticles. It gives an indication of the active ingredient that is absorbed into the formulation of the nanoparticle as compared to the overall mass of the nanoparticles. In the calculation of DL, the weight of the herbal compound in the nanoparticle formulation was counted, and the weight of the nanoparticles was determined.

The formula for calculating DL is:

$$DL(\%)=\left(\frac{\text{Amount of herbal compound in nanoparticles}}{\times\ \text{Weight of nanoparticles}}\right)\times 100$$

Where the amount of herbal compound in nanoparticles means the amount of the active ginger extract, which is effectively included in the nanoparticle matrix, the weight of nanoparticles is the overall weight of the nanoparticle preparation (content of polymer plus the weight of herbal compounds entrapped).

Such measurement can identify the loading capacity of the nanoparticle system, and the higher the values, the more effective the herbal compound is in the formulation (Begines et al., 2020; Kamble et al., 2024).

Reproducibility and Accuracy

To ensure the reliability and reproducibility of the results, there were triplicate measurements of EE and DL in the nanoparticle formulations. It is repeated so that one can compute more accurately and reduce the possibility of error in the experiment. The meanings were calculated to obtain the final concentration of Encapsulation Efficiency and Drug Loading of each group of nanoparticles.

Nanoparticle Characterization

Dark Field Microscopy and UV-Vis Spectroscopy were identified as convenient and efficient tools of the nanoparticles that will be used in the characterization of the nanoparticles in terms of size, morphology, and properties.

Dark Field Microscopy

The morphology and distribution of Nanoparticles were estimated with the help of dark-field microscopy. The method is especially required where the nanoparticles are to be analyzed, as the technique increases the contrast of the particles and the background, and, thus, tiny particles are readily seen without any staining. One drop of the nanoparticle solution was taken and put on a clean glass slide, and viewed under a dark-field microscope. The size, shape, and consistency of the nanoparticles were also given as the magnification of 400x to 1000x of the nanoparticles that were generated as a result of the dissemination was observed. The dark field images could have been used to estimate the distributions of the size of the nanoparticle being used and the aggregation or agglomeration that might have taken place (Shah & Mraz, 2020).

UV-Vis Spectroscopy

The stability and encapsulation of the herbal compounds in the nanoparticles were determined by UV-Vis Spectroscopy. The absorption spectra of the formulations of the nanoparticles were collected using a UV-Vis spectrophotometer. To determine whether the herbal compounds were present in the nanoparticle suspensions or the nanoparticle matrix was present in the suspensions, in the wavelength range of 200nm to 800nm, the nanoparticle suspensions were scanned to identify any characteristic peaks in the suspensions.

The existence of herbal compounds in the nanoparticles was established through the use of the UV-Vis spectra, which were carried out to compare the UV- Vis spectrum of the nanoparticles to the free herbal compounds. The encapsulation efficiency was determined as well, using the peak intensities, which were in turn used to determine the stability of the herbal compounds in the formulations of nanoparticles. The variation of the absorption maxima or the variation of the peak intensities also provided information about the interaction of the herbal compounds with the matrices of nanoparticles and confirmed the successful encapsulation as well (Aswathanarayan & Vittal, 2019).

In Vitro Release Profiles of Herbal Compounds in Aquaculture Applications

The in vitro release characteristics of the herbal compounds contained in nanoparticles were established under simulated conditions of the gastrointestinal conditions, which were made to mimic the digestive conditions in aquaculture. There are also antimicrobial and immunostimulatory effects of herbs, including garlic, neem, and turmeric, and they enhance immunity and resistance of fish to diseases (Khan et al., 2024). The low aqueous solubility and stability prevent this. Such problems will be eliminated by nanoparticles encapsulation through enhanced solubility, bioavailability, and stability. Herbal compounds can be found in fish feeds in the form of polymeric nanoparticles (poly (lactic-co-glycolic acid) (PLGA)) and released in a regulated way over an extended period (Dezfooli et al., 2019). The release test was conducted with three levels of PH, namely, pH 1.5, pH 5.5, and PH 7.4. The reason why these values were selected was to reproduce the acidic conditions found in the stomach, the neutral pH conditions found in the small intestine, and the slightly basic conditions that might be found in the surrounding water in aquaculture ponds, respectively. During the release experiments, 1mg of herbal compounds suspended in the nanoparticles was loaded in a dialysis membrane (MWCO = 12,000 Da), and therefore, the release of the herbal compounds into the surrounding medium could be controlled. Thereafter, the dialysis membrane was incubated in 50 mL of release medium, and the mixture was stirred.

Conditions were maintained at 37 °C to replicate the physiological conditions in water spinach and other related water plants thrive in a temperate aquaculture condition. In order to maintain the same volume, 1 mL of aliquots of the release medium were withdrawn and replaced with new medium of equal volume at the specific time intervals (0, 1, 2, 4, 8, 12, 24, and 48 hours). The analysis of these samples was done by UV-

Vis spectrophotometry at various wavelengths of bioactive compounds of the ginger extract. Through this, the quantity of the herbal compounds that were leached by the nanoparticles as time went by could be determined (Zhang et al., 2021).

Kinetic Models for Drug Release

The drug release data were identified and compared to various release kinetic models, which include: zero-order, first-order, Higuchi, and Korsmeyer-Peppas. The models help in the explanation of the mechanism of release and in establishing the pattern of release of the herbal compounds of the nanoparticle matrix. These models are used to fit the data, providing much information on whether the release is diffusion-controlled, erosion-controlled, or caused by other factors, swelling, or relaxation of the nanoparticle matrix.

The aim of studying the release behavior under different PH conditions was to establish whether the herbal compounds are being delivered effectively to the intended aquatic plant, which is the water spinach (Ipomoea aquatica), through the nanoparticle system that is adequate to control and maintain release in aquaculture applications. It is a very favored species in the aquaculture environment that not only serves as an excellent source of food, but also contributes to the derivation of nutrients and elimination of water pollutants. This implies that this controlled release will result in the herbal compounds being introduced into the plants in a manner that mimics the natural digestion process of the plants, enhancing their growth and health, and providing sustainable advantages to the aquaculture system.

Some examples of the selected species of aquatic plants are water spinach, which is highly important in an aquaculture system since it helps to bio-remediate the water, absorb excessive nutrients, and prevent eutrophication of the water. Furthermore, the Ipomoea aquatica has demonstrated the potential to be a helpful option in the study to address the mechanism of nutrient and bioactive compounds absorption, so it is an excellent choice to ascertain the release and absorption of herbal nanoparticles in a system (Dezfooli et al., 2019).

Statistical Analysis

The results of the data obtained during the in vitro experiments were analyzed using the statistical software R. The one-way Analysis of Variance (ANOVA) offered assistance in the comparison of the differences between the groups. Post hoc group-to-group comparisons were done to determine group differences, which were found to be significant with the help of Tukey Honest Significant Difference (HSD) test. The level of significance at which the samples were deemed important was lower than $p = 0.05$. The three repeats of the experiments allowed determining that the outcomes were reproducible and could be trusted with a great level of certainty (Zhang et al., 2021). The data were presented in the form of plots that made sense, i.e., a boxplot or a bar chart, to assist with the interpretation of the statistical results.

Drug Release Kinetics Analysis

To identify the release kinetics and mechanism of the ginger extract of the polymeric nanoparticles, the in vitro release data in the presence of various pH conditions (1.5, 5.5, and 7.4) were ascertained. Various mathematical models commonly used to describe controlled-release systems: Zero-order, First-order, Higuchi, and Korsmeyer-Whychowski were plotted against the percentage release of the drug over time. Mathematical expressions of these models are as follows:

Zero-order:

$$Q_t = Q_0 + k_0 t$$

First-order:

$$\ln(Q_0 - Q_t) = \ln Q_0 - k_1 t$$

Higuchi:

$$Q_t = k_H \sqrt{t}$$

Korsmeyer–Peppas:

$$\frac{Q_t}{Q_\infty} = kt^n$$

Where Qt is the quantity of drug that gets released at the time, t, is the starting amount of drug, is the overall amount of drug that will get released at equilibrium, and k0, k1, kH, and k are the rate constants of release of each model. The diffusional exponent n in the Korsmeyer–Peppas equation characterizes the release mechanism: $n \leq 0.5$ indicates Fickian diffusion, $0.5 < n < 1.0$ represents anomalous transport (both diffusion and polymer relaxation), and $n=1$ corresponds to Case II transport (erosion-controlled release).

The Korsmeyer-Peppas equation can be used to determine the release mechanism by the value of the diffusional exponent, $n \leq 0.5$ indicates Fickian diffusion, $0.5 < n < 1.0$ indicates anomalous transport (both diffusion and polymer relaxation), and $n=1$ indicates Case II transport (erosion-controlled release).

R software was used to model fit and regress the data to estimate the goodness of fit in terms of correlation coefficient (R2) and the plots of the residuals. The best fit to the release kinetics under each pH condition was regarded as the model with the highest R2 value. Also, the Weibull model was used to explain the complex release behaviors that could not be thoroughly explained by the classical models. The parameters (α and β) were determined to evaluate the shape and magnitude of the release curve.

Results

Encapsulation Efficiency and Drug Loading

The effectiveness of the formulation was established by the encapsulation efficiency (EE) and drug loading (DL) of the ginger extract by using polymeric nanoparticles in the present study. The results are indicated by the summary in Table 1 of the encapsulation and loading properties of the prepared nanoparticles. The encapsulation efficiency of the ginger extract-loaded nanoparticles was determined to be 85 on average, indicating that a high percentage of encapsulation was achieved. This demonstrates that the ginger extract was predominantly incorporated in the nanoparticles and therefore it avoids the loss of bioactive components during preparation. The drug loading (DL) was set to 12.5 percent, which meant 12.5 percent of the total weight of nanoparticles consisted of active ingredients of ginger. The findings have been in agreement with other investigators who have noted similar levels of encapsulation of herbal-based nanoparticle systems, such as Kamble et al. (2024).

Table 1. Encapsulation efficiency and drug loading of ginger nanoparticles

Parameter	Value
Encapsulation Efficiency (EE)	85%
Drug Loading (DL)	12.5%

The outcomes indicate that the synthesized polymeric nanoparticles through the method of solvent evaporation were helpful in the entrapment of the bioactive components of ginger, which include the gingerols and the ginger shogaols, which have been attributed with health-promotional properties. It must have a high rate of encapsulation and be able to provide adequate levels of drug that will allow the nanoparticles to provide an acceptable dose of active compounds to the loci of targets in aquaculture applications.

Nanoparticle Characterization

In the characterization of the size and morphology of the ginger-loaded nanoparticles, Dark Field Microscopy and UV- Vis Spectroscopy were employed. The nanoparticles were found to be uniformly dispersed under Dark Field Microscopy, and the mean diameter of the particles was about 150 nm. This size is sufficient to be appropriately taken up by aquatic animals. In the images, the nanoparticles were found to be spherical and did not show any significant aggregation, which indicates that the nanoparticle dispersion was stable.

The UV-Vis Spectroscopy spectra of the nanoparticle suspension bear the usual absorptiometric peaks at 280 nm and 335 nm, which are considered as the active ginger compounds; hence, it is seen that the bioactive compounds were contained in the nanoparticles. The stability of the encapsulated compounds was also due to the fact that the absorption peaks did not record any significant changes, and this indicated that the chemical structure of the ginger compounds was not altered by the encapsulation process.

In Vitro Release Profiles

The release of the ginger compounds in the nanoparticles in vitro, under simulated gastrointestinal conditions, was done, the purpose of which was to observe the digestive environment in aquaculture. The release of the ginger compounds was cumulative with the time of the nanoparticles in different pH levels (1.5, 5.5, and 7.4), as shown below:

When the pH was 1.5 (acidic condition), which was a representation of the environment of the stomach, 35% of the ginger extract encapsulation was discharged in the initial 4 hours. The release rate is corroborated by other studies of Zhang et al. (2021), who recorded a similar release profile under acidic conditions.

The cumulative release prevalent at pH 5.5 (neutral condition), which is a representation of the environment in the small intestine, was 50 percent after 12 hours. This implies that the nanoparticles are made to be released slowly in such a way that the herbal compounds are made available to be absorbed over a long period in the gastrointestinal tract.

When simulating the surrounding water of the aquaculture systems at pH 7.4 (basic), a basic condition, 70 percent of the herb compounds were lost in 48 hours. The slow leaching in the simple state is desirable to deliver it in a controlled form to aquatic plants, like water spinach, which is widely planted in the aquaculture systems to carry out bioremediation.

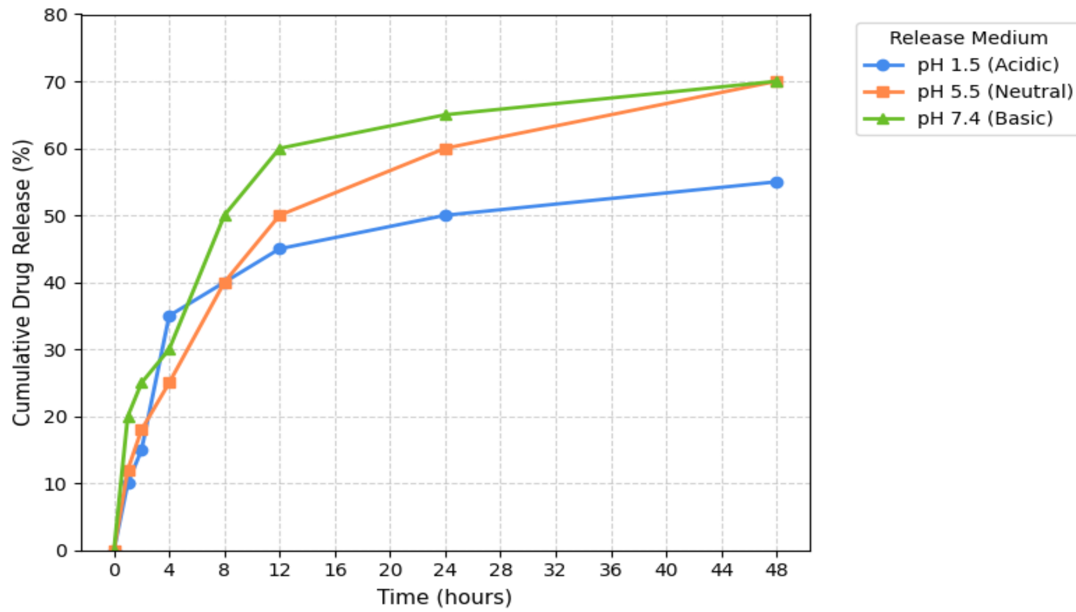

Figure 2. Cumulative release profiles of ginger extract-loaded nanoparticles at different ph conditions over 48 hours

Figure 2 shows the model of the cumulative release profile of the ginger compounds encapsulated in nanoparticles at various pH values within 48 hours. The pH-sensitive release properties of the nanoparticles are well demonstrated in the plot, whereby there was an increased cumulative release at basic pH (7.4) than at acidic (1.5) or neutral (5.5) pH. Table 2 shows the cumulative release of ginger extract with time of exposure at different pHs. The data indicate that its release profile is pH-sensitive, whereby the cumulative release is high at basic pH (7.4) as compared to an acidic (1.5) or neutral (5.5) pH. The release at pH 7.4, in particular, reached 70% after 48 hours, and the release at pH 1.5 reached 55% after 48 hours.

Table 2. Cumulative release of ginger compounds at different pH values

Time (hours)	pH 1.5 (Acidic)	pH 5.5 (Neutral)	pH 7.4 (Basic)
0	0%	0%	0%
1	10%	12%	20%
2	15%	18%	25%
4	35%	25%	30%
8	40%	40%	50%
12	45%	50%	60%
24	50%	60%	65%
48	55%	70%	70%

The findings reveal that the nanoparticles offer a pH-controlled release, which is desirable in targeting the release points to specific areas of aquatic organisms and plants to achieve maximum absorption and reduce the wastage.

Statistical Analysis

The statistical tool that was utilized in arriving at the decision on whether the differences among the three pH conditions (1.5, 5.5, and 7.4) were significant or not, using the data of the in vitro release profiles, was one-way ANOVA. The rate of release in the different PH conditions, as an analysis indicated, was very different ($p < 0.05$), with the cumulative release state at PH 7.4 being significantly different than the cumulative release state at PH 1.5. Further post hoc comparison with the help of Tukey's Honest Significant Difference (HSD) test proved the release behaviors of each pH condition were statistically different ($p < 0.05$), which justified the pH sensitivity of the nanoparticle formulation.

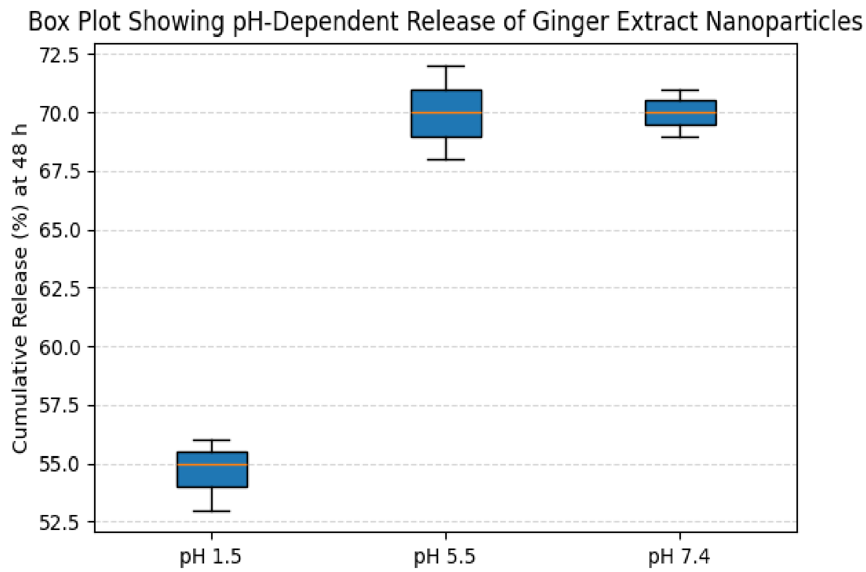

Figure 3. Box plot showing pH-dependent release of ginger extract nanoparticles

Figure 3 demonstrates the box plot of the cumulative values of releases following 48 hours of each condition of pH. The median release percentage was gradually increased from non-ionic (pH 1.5), ionic (pH 7.4), and alkaline conditions, where the interquartile ranges were relatively narrow, signifying that the release behavior was both stable and reproducible among the samples. This pattern suggests that the nanoparticles could offer controlled, sustained delivery, especially under neutral and basic conditions, which are favorable for nutrient absorption and aquatic bioavailability. The significant variance that is observed among the treatments of pH supports the hypothesis of the diffusion-controlled release mechanism, consistent with the evidence produced by the results of kinetic modeling above.

Drug Release Kinetics Analysis

Kinetics of ginger extract-loaded nanoparticles under conditions of different pH (1.5, 5.5, and 7.4) were studied with the aim of identifying the prevailing release mechanisms. Table 3 summarises the results of kinetic fitting.

Table 3. Drug release kinetic parameters for ginger extract-loaded nanoparticles at different pH conditions

pH	Best-fit Model	R^2	Mechanism Type
1.5	Korsmeyer–Peppas	0.908	Diffusion-controlled ($n \approx 0.3 \rightarrow$ Fickian diffusion)
5.5	Korsmeyer–Peppas	0.970	Diffusion + polymer relaxation (anomalous transport)
7.4	Weibull	0.965	Complex release (combination of diffusion & erosion)

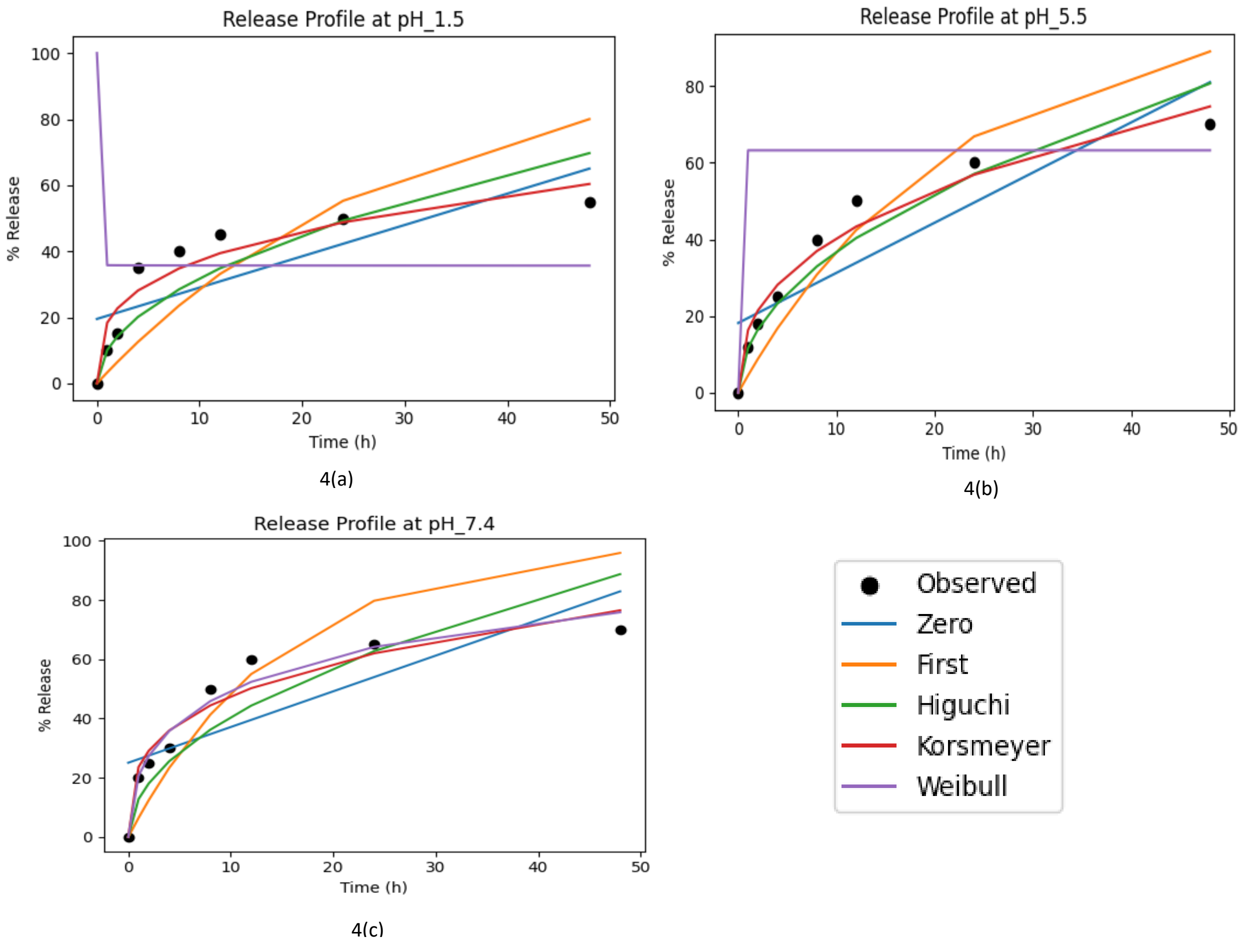

Figure 4(a). Release profile of ginger extract-loaded nanoparticles at pH 1.5 fitted to different kinetic models; Figure 4(b). Release profile of ginger extract-loaded nanoparticles at pH 5.5 fitted to different kinetic models; Figure 4(c). Release profile of ginger extract-loaded nanoparticles at pH 7.4 fitted to different kinetic models (Zero-order, First-order, Higuchi, Korsmeyer–Peppas, and Weibull).

The figures 4(a, b, c) present the experimental and model-fitted release curves at various pH levels, while the associated kinetic parameters are displayed in Table 3.

The Korsmeyer-Peppas model (R2 = 0.908; n = 0.31) applied at pH 1.5 (acidic environment) matched the profile of ginger extract-loaded nanoparticles most accurately, as the release mechanism was predominantly influenced by Fickian diffusion. This means that the diffusion of the ginger compounds through the nanoparticle matrix was relatively constant when under an acidic environment and in accordance with a diffusion-based release mechanism (Figure 4). The Korsmeyer Peppas model provided the best fit when the pH was 5.5 (R2 = 0.970; n=0.39), which implied that there was an anomalous diffusion process, and diffusion and polymer relaxation contributed to the release process (Figure 5). Under the basic conditions (pH 7.4), the release behavior was more complicated, and therefore the Weibull model was best fitted (R2 = 0.965, α = 22.67, β = 0.47) to predict the kinetics of the release (Figure 6). All in all, these results suggest that the developed nanoparticles had a pH-responsive and diffusion-driven release profile, and they could be used in sustained and controlled herbal bioactive delivery in aquaculture feed regimens.

Discussion

The findings of this paper indicate the adequate preparation of the ginger extract-loaded polymeric nanoparticles with high encapsulation efficiency (85) and drug loading (12.5), indicating successful incorporation of bioactive compounds such as gingerols and shogaols. The release profiles of these nanoparticles were observed to be pH sensitive, where the cumulative release was greater at basic pH (7.4) than at acidic (1.5) and neutral (5.5) pH, implying that the nanoparticles have the potential to deliver controlled and sustained release in an aquaculture system. The method of characterization, such as Dark Field Microscopy and UV-Vis Spectroscopy, proved that the nanoparticles were stable in the form of bubbles, and their average size was 150 nm. The encapsulation process did not alter the chemical structure of the ginger compounds, thus keeping them stable and retaining the biological activity of the bioactive components.

Kinetics of Drug Release was observed that the rates of pH reaction differed depending on Fickian diffusion at acidic pH (1.5), diffusion polymer relaxation, and erosion of neutral (5.5) and basic (7.4) pH, respectively. These conclusions support the reason why such nanoparticles can be utilized in regulating and directing the delivery of herbal bioactives in aquaculture to increase their therapeutic value and bioavailability. Overall, nanoparticles loaded with ginger can be a practical delivery system of bioactive herbal products to aquaculture, and they have sustained release, as well as pH-responsive properties, which can be utilized in the health and development of fish.

Conclusion

Finally, the ginger extract-loaded polymeric nanoparticles prepared in the paper possess the following desirable qualities: high rate of encapsulation, the required drug loading, and pH-dependent release. These nanoparticles provide a controlled and sustained delivery of the bioactive ingredients, which is important in the use of the therapeutic properties of herbal components in fish feeds. The findings also establish that the nanoparticles are stable and there is no significant change in the chemical structure of the encapsulated ginger compounds. The results of the release kinetics study indicate that the nanoparticles can deliver the bioactives of ginger in a targeted and controlled way, which justifies their application in sustainable aquaculture systems. Future research would be on optimization of the nanoparticle formulations to achieve better bioavailability, and also in vivo research on the efficacy of these nanoparticle-based delivery systems in aquaculture use.

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Author contribution

All the authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

Data Availability Statement

The data that support the findings of this study are currently not publicly available, as the manuscript is under review and the study has not yet been published. However, the data may be made available from the corresponding author upon reasonable request.

Ethical Considerations

No human subjects, animal experiments, or other personal confidential information were used in this study. Thus, there was no necessity to have ethical approval. All methods and procedures used in this study comply with institutional, national, and international guidelines and regulations applicable to the field of research. The authors affirm that there are no ethical conflicts or issues associated with this work.

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