



The effect of nanoparticles on plankton dynamics: A mathematical model

Sourav Rana^a, Sudip Samanta^b, Sabyasachi Bhattacharya^c, Kamel Al-Khaled^d,
Arunava Goswami^c, Joydev Chattopadhyay^{c,*}

^a Department of Statistics, Visva-Bharati University, Santiniketan, West Bengal 731235, India

^b Department of Biomathematics and Game Theory, University of Warsaw, ul. Banacha 2, 02-097 Warszawa, Poland

^c Agricultural and Ecological Research Unit, Indian Statistical Institute, 203, B. T. Road, Kolkata 700108, India

^d Department of Mathematics and Statistics, Sultan Qaboos University, P.O. Box 36, Al-Khod 123, Oman

ARTICLE INFO

Article history:

Received 26 October 2013

Received in revised form 22 October 2014

Accepted 2 November 2014

Available online 6 November 2014

Keywords:

Phytoplankton

Zooplankton

Nanoparticles

Mathematical model

Functional responses

Stability analysis

Bifurcation

ABSTRACT

A simple modification of the Rosenzweig–MacArthur predator (zooplankton)–prey (phytoplankton) model with the interference of the predators by adding the effect of nanoparticles is proposed and analyzed. It is assumed that the effect of these particles has a potential to reduce the maximum physiological per-capita growth rate of the prey. The dynamics of nanoparticles is assumed to follow a simple Lotka–Volterra uptake term. Our study suggests that nanoparticle induce growth suppression of phytoplankton population can destabilize the system which leads to limit cycle oscillation. We also observe that if the contact rate of nanoparticles and phytoplankton increases, then the equilibrium densities of phytoplankton as well as zooplankton decrease. Furthermore, we observe that the depletion/removal of nanoparticles from the aquatic system plays a crucial role for the stable coexistence of both populations. Our investigation with various types of functional response suggests that Beddington functional response is the most appropriate representation of the interaction of phytoplankton–nanoparticles in comparison to other widely used functional responses.

© 2014 Elsevier Ireland Ltd. All rights reserved.

1. Introduction

Recently, the field of nanoparticles (NPs) has grabbed the attention of researchers from different scientific communities, like, Biology, Physics, Chemistry, Nanotechnology, etc. Though NPs have a wide range of applications, sometimes it may affect living organisms, human to marine plankton. Kokate et al. (2012) have explored that human immune cells are susceptible to the cytotoxicity of zinc oxide (ZnO) NPs. A report by the Scientific Committee on Consumer Safety (SCCS, 2012) revealed the presence of nanomaterials in cosmetics and sunscreens, although their risks to human health are still unknown. In their study, Oszlánczi et al. (2011) concluded that diesel NPs can damage the cardiovascular system of the mouse. In contrast, Miglietta et al. (2011) have studied the ecotoxicological impact of several types of NPs on marine organisms. The potential toxicity of various types of NPs to aquatic organisms, including plants, fungi, algae, invertebrates and fish have been

reported in the last few years (for an extensive review see Perez et al., 2009; Kahru and Savolainen, 2010; Stevenson et al., 2013; Castro-Bugallo et al., 2014; Das et al., 2014).

It is well documented that NPs are found in increasing numbers of products (like, drug delivery, cancer treatment, cosmetics, sunscreens, garments, paints, lithium-ion battery, fertilizer, processed foods, etc.), which ultimately release into the aquatic environment. This may occur during production, use or disposal, either directly (e.g. as a result of accidents) or via waste water. Moreover, NPs can be released through the natural processes like forest fires, volcanic activities, weathering, formation from clay minerals, soil erosion by wind and water, or dust storms from desert (Smita et al., 2012). These NPs are quite heterogeneous in size and can be transported over thousands of kilometers and remain suspended in the air for several days (Smita et al., 2012) and ultimately goes to the sea water. After any release of NPs, it is ultimately submerged into seawater, so it is a very important issue to study their behavior in seawater for the potential hazards creating by them to living organisms. The contact between NPs and marine organisms mostly depends on their dispersion and behavior in aqueous systems, and the risk is often related to their surface speciation (Labille and Brant,

* Corresponding author. Tel.: +91 33 25753231; fax: +91 33 25773049.
E-mail address: joydev@isical.ac.in (J. Chattopadhyay).

2010). Internalization and/or attachment of nanoparticles to phytoplankton cells causes the growth suppression among a wide range of phytoplankton species (Miao et al., 2009, 2010; Miller et al., 2012).

Griffitt et al. (2008) also tested the toxicity of silver, copper, aluminum, nickel, and cobalt NPs to zebra fish, daphnids, and algal species. Recently, it was discovered that titanium dioxide (TiO₂) NPs have substantial toxic effect on marine phytoplankton when subjected to normal levels of ultraviolet light exposure. Miller et al. (2012) experimentally measured the toxicity of NPs (TiO₂) in terms of population growth suppression. In their experiment, they used four predominant species of phytoplankton (*Isochrysis galbana*, *Thalassiosira pseudonana*, *Dunaliella tertiolecta* and *Skeletonema costatum*) representing three major groups, the diatoms (Class: Bacillariophyceae), green algae or chlorophytes (Class: Chlorophyceae), and the prymnesiophytes (Class: Prymnesiophyceae). They designed experiments with two orthogonal treatments: UV exposure (two levels: exposed, blocked), and TiO₂ concentration (five levels: 0, 1, 3, 5, 7 mg L⁻¹). Significant suppression of population growth occurred for three out of four species in the UV-exposed treatment. They concluded that the NPs can significantly reduce the population growth of the above mentioned first three species in the presence of ultraviolet-exposed treatment. They have suggested that NP internalization is possibly one of the reasons influencing the algal growth. Miao et al. (2010) also demonstrated that Ag-ENs can be taken and accumulated inside the algal cells, where they exerted their toxic effects. Therefore, nanoparticle internalization may be an alternative pathway through which algal growth can be influenced. Significant toxicity to the freshwater alga *Ochromonas danica* was observed in the higher Ag-EN concentration treatments. Cell growth was inhibited by 18.8, 40.3, and 100% when Ag-EN concentration was 139.1, 185.4, and 278.1 μM (Ag element based molarity), respectively. They also revealed that zinc oxide-engineered NPs were toxic to marine phytoplankton. Furthermore, internalization of CuO, NPs was observed in the intact algal cells using high resolution transmission electron microscope (HRTEM), and the internalization was enhanced by Suwannee river fulvic acid (SRFA) (Wang et al., 2011). Moreover, nanoparticles suspended in the water can easily attach to phytoplankton cell membranes and lower the growth of phytoplankton. The most important processes like agglomeration, aggregation, dissolution and chemical reactions, including the oxidation or reduction, ligand exchange and formation of new solid phases have significant effects on the fate of NPs in aquatic environments (Handy et al., 2008; Klaine et al., 2008; Navarro et al., 2008a). Recently, Castro-Bugallo et al. (2014) experimentally showed that zinc oxide (ZnO) and yttrium oxide (Y₂O₃) have the toxic effect on marine microalgae. They also observed that population growth rate was the most susceptible variable to the acute toxic effect of the both NPs as measured in terms of numbers of cells and biomass. Stevenson et al. (2013) investigated the effect of citrate-coated silver nanoparticles (AgNPs) on a freshwater alga *Chlamydomonas reinhardtii* at different phases of batch culture growth and showed that the AgNPs are most toxic to cultures in the early phases of growth. Das et al. (2014) also investigated the effects of AgNPs and its interactions with phosphorus (P) supply on the growth of phytoplankton. They observed that AgNPs reduce the maximum phytoplankton growth rates by 11–85%. They suggested that the fate and toxicity of AgNP will vary with the phosphorus pollution level in aquatic ecosystems. The above discussion clearly indicates that the release of NPs in an aquatic environment becomes a great concern due to their negative impact on ecological systems (Maynard et al., 2006). Most of the experimental studies demonstrated the interactions between NPs and phytoplankton, and their consequences on individual and/or population level, but the effect of nanoparticle on the aquatic food chain not yet studied properly. Therefore, it is interesting to study the interaction of nanoparticles

and phytoplankton and its consequences on the aquatic food chain. As far our knowledge concern this is the first attempt to describe the interaction between phytoplankton and NPs through mathematical modeling. To start the modeling aspects of such dynamics, we restrict ourselves in this study with a phytoplankton–zooplankton system under the influence of NPs.

Phytoplankton is the primary producer of freshwater and marine systems. It supplies energy and nutrients to the higher trophic levels (herbivore/omnivore) of the food chain. It is well documented that NPs have a negative impact on primary producer of the aquatic food chain. Naturally, the studies related to the interaction of phytoplankton and NPs need in depth investigations both from theoretician and experimentalists.

In the present article, we hypothesize that NPs reduce the intrinsic growth rate of phytoplankton population. The growth rate of phytoplankton is inversely proportional to the concentration of NPs in the aquatic system. To study the effect of NPs on the plankton dynamics, we consider a simple phytoplankton–zooplankton model and introduce a term representing the phytoplankton–nanoparticle interactions in the model system. The model analysis will help us to understand the effect of NPs on plankton dynamics. It is wise to mention that in our study, we concentrate only the growth reduction of the phytoplankton due to NPs but not for zooplankton. The basic aim of the investigation is to observe the dynamics of a simple phytoplankton–zooplankton system under the influence of NPs.

The paper is organized as follows. In the next section, we present the mathematical model and the boundedness of its solutions. In Section 3, we perform local stability analysis of all equilibrium points. We also find out the stability conditions for different functional responses and the effect on NPs on the equilibrium densities. In Section 4, we study the conditions for the existence of Hopf bifurcation around the interior equilibria along with its direction and stability. Numerical simulations are performed in Section 5. Finally, we discuss our results and conclude our findings.

2. The mathematical model

To study the impact of NPs on a phytoplankton–zooplankton system, first we consider a simple predator–prey model where the phytoplankton and zooplankton population represents prey and predator populations respectively. The mathematical model is represented by a system of ordinary differential equation as follows:

$$\begin{aligned} \frac{dP}{dt} &= rP \left(1 - \frac{P}{K} \right) - \frac{cPZ}{b + \gamma P + \alpha Z}, \\ \frac{dZ}{dt} &= \frac{dcPZ}{b + \gamma P + \alpha Z} - \mu Z, \end{aligned} \quad (2.1)$$

Here P denotes the density of phytoplankton as prey and Z denotes the density of zooplankton as predator populations at time t . In the absence of zooplankton, the phytoplankton population follows the logistic growth with an intrinsic growth rate r and carrying capacity K . Zooplankton predate phytoplankton on Beddington functional response (Beddington, 1975) with predation rate c , saturation constant b , α scales the impact of the predator interference and γ is a food weighting factor. The parameter d is an efficiency of converting prey intake into new predator, and μ is the natural mortality rate of the predator. Here we chose the Beddington functional response (FR) since it is more generalized and the other widely used functional responses namely Holling Type I and Holling Type II can be derived from it.

Recent experimental studies on NPs have revealed the fact that they have toxic effects on freshwater and marine algae. Interaction of NPs and phytoplankton results lower growth and less photosynthesis in phytoplankton species (Navarro et al., 2008b;

Download English Version:

<https://daneshyari.com/en/article/2075906>

Download Persian Version:

<https://daneshyari.com/article/2075906>

[Daneshyari.com](https://daneshyari.com)