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Review

Environmentally relevant approaches to assess nanoparticles ecotoxicity: A review

Agathe Bour[a,b], Florence Mouchet[a,b], Jérôme Silvestre[a,b], Laury Gauthier[a,b], Eric Pinelli[a,b,*]

[a] Université de Toulouse; UPS, INP; EcoLab (Laboratoire d'écologie fonctionnelle et environnement); ENSAT, Avenue de l'Agrobiopôle, F-31326 Castanet-Tolosan, France
[b] CNRS; EcoLab (Laboratoire d'écologie fonctionnelle et environnement), F-31326 Castanet-Tolosan, France

HIGHLIGHTS

- Integrated ecotoxicity of NPs from organism to community level is reviewed.
- Trophic chains allow determining the implication of trophic route in NP toxicity.
- The use of microcosms and mesocosms allows studies at larger scale.
- Data concerning NP fate and effects in environmental conditions are lacking.

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ABSTRACT

Despite the increasing production and use of nanoparticles (NPs), there is a lack of knowledge about their environmental fate and ecotoxicity. Studies in environmentally relevant conditions are necessary to better assess these parameters, but such studies are rather rare. The present work represents first time that studies on engineered NPs using environmentally relevant exposure methods have been reviewed. These exposure methods differ from standardized protocols and can be classified into three groups: experimental trophic chains that allow study of the trophic route, multi-species exposures under laboratory conditions that allow for complex but controlled exposure and outdoor exposures that are more similar to environmentally realistic conditions. The majority of studies of micro- or mesocosms have focused on NP partitioning and bioaccumulation. The other major parameter that has been studied is NP ecotoxicity, which has been assessed in single species, in single species *via* the trophic route, and at the community level. The induction of biochemical defense systems, immunomodulation, effects on growth and reproduction, behavioral alterations and mortality have been used as indicators of major toxicity, depending on the species studied. The major effects of NPs on both microbial and algal communities include modifications of community compositions and diversities, decreased biomass and changes in community activities.

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* Corresponding author at: EcoLab, campus ENSAT, Avenue de l'Agrobiopôle, 31326 Castanet-Tolosan, France. Tel.: +335 34 32 39 45; fax: +335 34 32 39 01.
E-mail address: pinelli@ensat.fr (E. Pinelli).

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1. Introduction

Recent decades have seen the emergence of manufactured nanoparticles (NPs), and the substantial advantages of NPs are now widely recognized. These nanoscale materials have been produced for decades, but industrial large-scale production began only in recent years. Piccinno et al. [1] estimated the worldwide production of four metal-oxide NPs and carbon nanotubes (CNTs) to be between 100 and 1000 t/year and up to 10,000 t/year for TiO_2 NPs. Nanoparticles are used in various fields, such as medicine, electronics and computers, the automotive industry, and in more than 1800 consumer products. This latter number has doubled in the last five years (http://www.nanotechproject.org). Several studies have modeled the potential release of NPs into the environment [2–5] and shown that NPs are expected to be found in the different environmental compartments (*i.e.*, soil, water, air, and landfills).

Thus, it is of primary importance to elucidate the potential effects of nanomaterials on the health of ecosystems. The literature provides an increasing number of studies about the toxicities [6], environmental behaviors and ecotoxicities of NPs [7,8], particularly the most widely used NPs, such as TiO_2 [9] and silver NPs [10]. However, most of the ecotoxicity studies have been conducted under controlled laboratory conditions and with single-species exposures to determine whether NPs are toxic to a specific species or to understand the toxicity mechanisms. Although essential, these studies do not account for complex environmental parameters; *e.g.*, such as complex matrices, real weather conditions, multi-species exposures, competition, predation and trophic relations. To better understand the actual effects of nanoparticles on ecosystems, recent studies have tended to reproduce more environmentally relevant exposure scenarios *via* the use of different exposure methods and systems.

The first goal of this review is to provide an overview of the methods and systems that are currently used in the field of ecotoxicology and enable integrated studies of engineered NP ecotoxicity in both aquatic and terrestrial environments. Data regarding laboratory exposures involving single species are not presented in the present review; rather, this review focuses on experiments related to multiple trophic levels, simultaneous exposures of multiple-species, and systems that allow for the study of complex biotic and/or abiotic factors. The second part of this review highlights the different types of information that such studies can provide and presents the main findings of these studies. Finally, the contribution of integrated ecotoxicity studies to the furthering of our knowledge about NP toxicity and remaining gaps and perspectives for future studies are discussed in the third part.

2. Organismal uptake and accumulation of NPs

Several notions concerning NP accumulation in organisms are used in the present review. The key terms are defined in this section.

Bioaccumulation refers to the accumulation of a contaminant in an organism, and all routes of exposure are considered. Bioaccumulation thus results from direct exposure (*e.g.*, from the water, soil and air) and exposure from contaminated food. Bioaccumulation can be quantitatively determined with the bioaccumulation factor (BAF), which is defined as the ratio of a contaminant concentration in an organism to the contaminant concentration in the environment. The BAF is typically determined in field experiments in which no distinction is made between uptake due to food and uptake due to direct exposure.

Bioconcentration refers to the accumulation of a contaminant in an organism solely from its environment (*i.e.*, water, soil and air). In contrast to bioaccumulation, only direct contact is considered (*e.g.*, skin contact, respiration), and contamination from food is excluded from assessments of bioconcentration. Thus, bioconcentration can only be determined in laboratory experiments. Bioconcentration can be quantitatively determined with the bioconcentration factor (BCF), which is defined as the ratio of a contaminant concentration in an organism to the contaminant concentration in the environment.

Biomagnification: The term biomagnification is used when the contaminant concentration in an organism is higher than the concentration in an organism of a lower trophic level. The biomagnification factor (BMF) is defined as the ratio of a contaminant concentration in a predator to the concentration in its prey. BMFs exceeding one generally indicate the occurrence of biomagnification in a trophic chain.

The *trophic transfer factor* (TTF) is the ratio of the concentration of a substance in an organism's tissue to the concentration of that substance in organism's food.

When bioaccumulation, bioconcentration, bioamplification and TTF are assessed in ecotoxicity studies, it is important to ensure that only the portion of the contaminant that has actually accumulated considered. Contaminants present on the surface but not absorbed inside the organism must not be taken into account. Similarly, if a contaminant ingested by an organism can be eliminated by simple excretion, it must not be taken into account despite its temporary presence in the digestive tract. Therefore, following the exposure period, organisms should be rinsed and allowed to depurate; *i.e.*, they should be placed in a non-contaminated environment long enough for complete excretion to occur so that only the absorbed contaminant is left in the organism.

Absorption by the organism can result from several processes. Contaminants can directly enter the cells (*e.g.*, intestinal, skin or gill cells) or can cross epithelial barriers through intercellular junctions without entering the cells to enter the blood circulation and then be distributed to the whole organism. In the particular case of NPs, contaminants can also be trapped inside the digestive tract and prevent normal exchanges (*e.g.*, nutrient uptake), which can result in physiological impairments even though the contaminant is not absorbed. Therefore, it is relevant to consider these NPs as accumulated, given that they cannot be eliminated by simple excretion.