Biofuel Research Journal 39 (2023) 1901-1932

Biofuel Research Journal

Journal homepage: www.biofueljournal.com

Review Paper

Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review

Homa Hosseinzadeh-Bandbafha[1,2,‡], Hamed Kazemi Shariat Panahi[3,4,‡], Mona Dehhaghi[4], Yasin Orooji[5], Hossein Shahbeik[6,7], Omid Mahian[8,9], Hassan Karimi-Maleh[10,11], Alawi Sulaiman[12], Changtong Mei[3], Mohammadali Kiehbadroudinezhad[13], Abdul-Sattar Nizami[14,15], Gilles G. Guillemin[4], Su Shiung Lam[7,16], Wanxi Peng[6], Xiangmeng Chen[1,*], Ki-Hyun Kim[17,*], Mortaza Aghbashlo[18,*], Meisam Tabatabaei[7,19,*]

[1]*Henan Province International Collaboration Lab of Forest Resources Utilization, School of Science, Henan Agricultural University, Zhengzhou 450002, China.*

[2]*Biofuel Research Journal (BRTeam), Terengganu, Malaysia.*

[3]*Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, College of Materials Science and Engineering, Nanjing Forestry University, Nanjing 210037, China.*

[4]*Centre for Motor Neuron Disease Research, Macquarie Medical School, Faculty of Medicine, Health and Human Sciences, Macquarie University, Sydney, NSW, Australia.*

[5]*College of Geography and Environmental Sciences, Zhejiang Normal University, Jinhua 321004, China.*

[6]*Department Henan Province Engineering Research Center for Forest Biomass Value-added Products, School of Forestry, Henan Agricultural University, Zhengzhou, 450002, China.*

[7]*Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP), Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.*

[8]*Zhejiang Provincial Engineering Research Center for the Safety of Pressure Vessel and Pipeline, Faculty of Mechanical Engineering and Mechanics, Ningbo University, Ningbo 315211, China.*

[9]*Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 634045, Tomsk, Russia.*

[10]*School of Resources and Environment, University of Electronic Science and Technology of China, P.O. Box 611731, Xiyuan Ave, Chengdu, China.*

[11]*School of Engineering, Lebanese American University, Byblos, Lebanon.*

[12]*Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia.*

[13]*Division of Engineering, Saint Mary's University, Halifax, NS B3H 3C3, Canada.*

[14]*Sustainable Development Study Centre, Government College University, Lahore, Pakistan.*

[15]*Center of Excellence in Environmental Studies (CEES), King Abdulaziz University, Jeddah, Saudi Arabia.*

[16]*Department of Chemical Engineering and Materials Science, Yuan Ze University, Taoyuan, Taiwan.*

[17]*Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-Ro, Seoul, 04763, South Korea.*

[18]*Department of Mechanical Engineering of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran.*

[19]*Department of Biomaterials, Saveetha Dental College, Saveetha Institute of Medical and Technical Sciences, Chennai 600 077, India.*

* Corresponding authors at:
E-mail address: meisam.tabatabaei@umt.edu.my & meisam_tab@yahoo.com (Meisam Tabatabaei); maghbashlo@ut.ac.ir (Mortaza Aghbashlo); kkim61@hanyang.ac.kr (Ki-Hyun Kim); xmchen0610@163.com (Xiangmeng Chen)

‡: *These authors contributed equally.*

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

HIGHLIGHTS

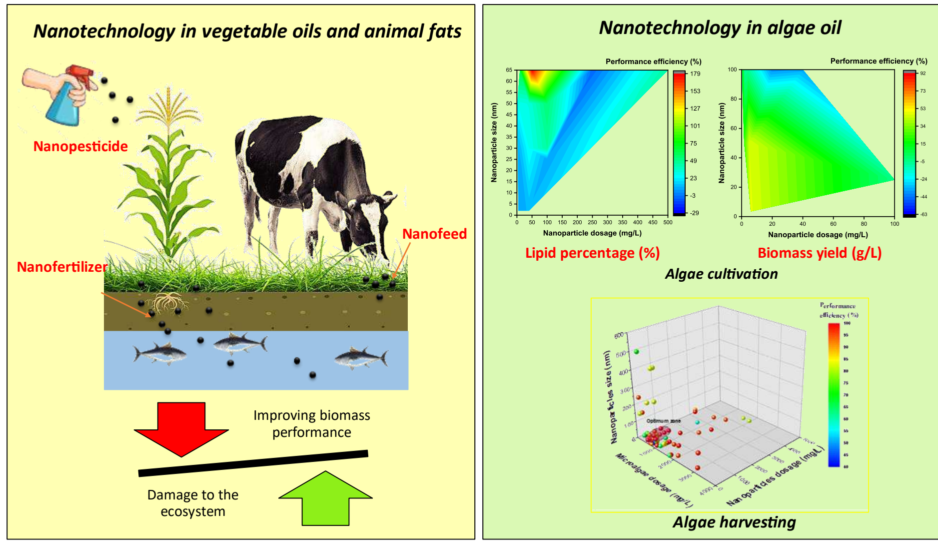
➢The potential of nanotechnology in biodiesel feedstock production is critically discussed.

➢The use of nanofertilizers and nanopesticides in oil crop breeding is fully illustrated.

➢Nanomaterials for boosting microalgal oil yield and biomass harvesting are scrutinized.

➢Health/ecological aspects of nanomaterials in biodiesel feedstock production are covered.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 May 2023
Received in revised form 2 July 2023
Accepted 2 August 2023
Published 1 September 2023

Keywords:
Biodiesel
Nanotechnology
Feedstock production
Oil crops
Microalgae oil
Animal fat

ABSTRACT

Sustainable socio-economic development largely depends on the sustainability of the energy supply from economic, environmental, and public health perspectives. Fossil fuel combustion only meets the first element of this equation and is hence rendered unsustainable. Biofuels are advantageous from a public health perspective, but their environmental and economic sustainability might be questioned considering the conflicts surrounding their feedstocks, including land use change and fuel *vs.* food conflict. Therefore, it is imperative to put more effort into addressing the downsides of biofuel production using advanced technologies, such as nanotechnology. In light of that, this review strives to scrutinize the latest developments in the application of nanotechnology in producing biodiesel, a promising alternative to fossil diesel with proven environmental and health benefits. The main focus is placed on nanotechnology applications in the feedstock production stage. First, the latest findings concerning the application of nanomaterials as nanofertilizers and nanopesticides to improve the performance of oil crops are presented and critically discussed. Then, the most promising results reported recently on applying nanotechnology to boost biomass and oil production by microalgae and facilitating microalgae harvesting are reviewed and mechanistically explained. Finally, the promises held by nanomaterials to enhance animal fat production in livestock, poultry, and aquaculture systems are elaborated. Despite the favorable features of using nanotechnology in biodiesel feedstock production, the presence of nanoparticles in living systems is also associated with important health and environmental challenges, which are critically covered and discussed in this work.

Contents

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

Abbreviations

CNM	Carbon-based nanomaterials
CNTs	Carbon nanotubes
DNA	Deoxyribonucleic acid
ENPs	Engineered nanoparticles
Fe_3O_4	Iron(II,III) oxide
MWCNTs	Multi-wall carbon nanotubes.
ROS	Reactive oxygen species
ZVI	Zero-valent iron
CNM	Carbon-based nanomaterials

1. Introduction

Although most scenarios developed by the governments are currently designed based on the fact that demands for energy in various sectors are on the rise, there are many arguments concerning how the role of fossil fuels should be minimized given the undesirable environmental and health effects, with global warming and climate change placed at their epicenter (Zhou and Feng, 2017). Sustainable production of eco-friendly alternatives to fossil fuels is the main remedy to this challenge (Dueso et al., 2018). Besides offering improved environmental impacts, biofuels are also associated with other benefits, including rural job creation, foreign exchange savings, and greater energy security (Bluhm et al., 2012).

Biodiesel is considered the most promising and acceptable among biofuels due to its reproducibility, biodegradability, non-toxicity, and sulfur-free nature. Biodiesel highly resembles diesel in terms of physicochemical properties, eliminating the need for considerable engine modifications. Biodiesel combustion in diesel engines, either in pure or blended form with diesel, reduces some of the major exhaust emissions, particularly particulate matter and carbon monoxide (Nabi et al., 2009). The production cycle of this alternative fuel, including oil feedstock production, oil extraction, and biodiesel production, is also a well-understood process with available technologies at a commercial scale (Nigam and Singh, 2011).

Generally, biodiesel is produced from three main generations of feedstock, including first-generation feedstock, i.e., vegetable oil (Demirbaş, 2002), second-generation feedstock, i.e., animal fats and waste oils (Goodrum et al., 2003), and third-generation feedstocks, i.e., microbial and microalgal oil (Ray et al., 2022). Oily vegetables and crops (i.e., first-generation) are the main feedstock for commercial biodiesel production (Demirbas, 2002). More than 350 oily vegetables and crops are recognized under different soil and climate conditions as feedstocks for biodiesel production (Ghazali et al., 2015). Vegetable oils are attractive not only because of their renewability but also because they hold an energetic content close to diesel fuel (Demirbas, 2005). Nevertheless, these feedstocks face serious criticism as their production has led to global land use change (deforestation) and food *vs.* fuel conflict. Despite the emergence of higher-generation biodiesel feedstock and its criticism, the biodiesel production industry worldwide relies predominantly on oily vegetables and crops. Therefore, efforts are focused on boosting their productivity to diminish their negative environmental footprints.

Traditionally, fertilizers and pesticides are used to increase crop yield (Zhao et al., 2016a), but they are also largely attributed to serious human health and environmental burdens (Sharma and Singhvi, 2017). A major second-generation biodiesel feedstock is animal fat. This feedstock is generally regarded as a more sustainable option than the first-generation feedstock from both environmental and economic points of view, but some health concerns, for example, the transmission risk of bovine spongiform encephalopathy by beef tallow has limited substantial biodiesel production from this low-cost feedstock. Finally, microalgae, the main third-generation biodiesel feedstock, offers many advantages, such as high lipid contents, high growth rate, and photosynthesis rate (Duran et al., 2018). Microalgae can also grow in non-agricultural land with waste and saline waters (Zhu et al., 2017) without pesticides or herbicides (Chiaramonti et al., 2017). However, increasing microalgal biomass and oil yield and enhancing algal biomass harvesting are still among the main challenges compromising the overall feasibility of using this promising biodiesel feedstock.

Among the technologies offered to overcome the obstacles faced in enhancing the biodiesel feedstocks, "nanotechnology" or, more specifically, using nonmaterial (<100 nm in size) is regarded as a cost-effective tool (Abdin et al., 2013). Compared with an equal weight of macroscale materials, not only do nanoscale matters have a surface area of several hundred times, but also their strength, tenacity, electricity, and elasticity are enhanced (Zhang et al., 2013). Because of the unique properties of nanomaterials, by the early 2000s, nanotechnology found its way into the marketplace and allowed manufacturers to improve their production (Garimella and Eltorai, 2017). Focusing on nanotechnology applications in the biodiesel production chain, there is a significant potential to improve feedstock production. Specifically, nanotechnology can enhance feedstock yield in producing vegetables as feedstock. This improvement can be attributed to the capacity of nanomaterials to more efficiently supply nutrients and pesticides for farming purposes (Shang et al., 2019). Studies show that nanomaterials can increase biomass growth and physiological processes such as photosynthetic activity, nitrogen metabolism, and protein level in microalgal species (Eroglu et al., 2013). However, the presence of nanoparticles in living systems is attributed to serious health and environmental challenges.

This work offers a state-of-the-art review of the application of nanotechnology for biodiesel feedstock production. First, it discusses the opportunities and limitations of nanotechnology applications in vegetable oil production. It then critically explores the nanotechnology applications and their challenges in microalgal oil production. Third, recent findings about the application of nanotechnology in animal fat production are scrutinized. To our knowledge, this paper is the most comprehensive work providing a thorough picture of the opportunities and limitations of nanotechnology applications in biodiesel feedstock production. **Table 1** compares this review paper with previous review papers published on the nanotechnology application for biodiesel feedstock production.

Table 1.
Comparison between the current review paper and previously published review papers on the application of nanotechnology in biodiesel feedstock production.

Reference	Type of feedstock		
	Animal fats	Algal oils	Vegetable oils
Mathimani and Mallick (2018)	✗	✓	✗
Nguyen et al. (2019)	✗	✓	✗
Goh et al. (2019)	✗	✓	✗
Yin et al. (2020)	✗	✓	✗
Sarkar et al. (2021)	✗	✓	✗
Zhao et al. (2022)	✗	✓	✗
Lau et al. (2022)	✗	✓	✗
Vignesh et al. (2022)	✗	✗	✓
Reetu et al. (2023)	✗	✓	✗
Rana and Prajapati (2023)	✗	✓	✗
This review	✓	✓	✓

✓: Included, ✗: Not-included

2. Nanotechnology applications in feedstock production

Based on feedstocks, biodiesel is classified into five different generations/categories (**Fig. 1**). All these oil feedstocks face numerous production challenges. For instance, applying chemical fertilizers and pesticides in vegetable oil production causes significant health and environmental problems. Some of the mentioned challenges can be potentially resolved using nanotechnology.

2.1. Vegetable oils

Generally, oily vegetables and crops (edible and non-edible) are the main feedstocks for biodiesel production. Over 350 oily vegetables and crops are currently cultivated worldwide as biodiesel feedstocks (Ghazali et al., 2015). Edible vegetable oils are renewable resources with energy values close to diesel fuel (Demirbas, 2005). However, their application in the biodiesel industry has triggered serious competition with food commodities

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

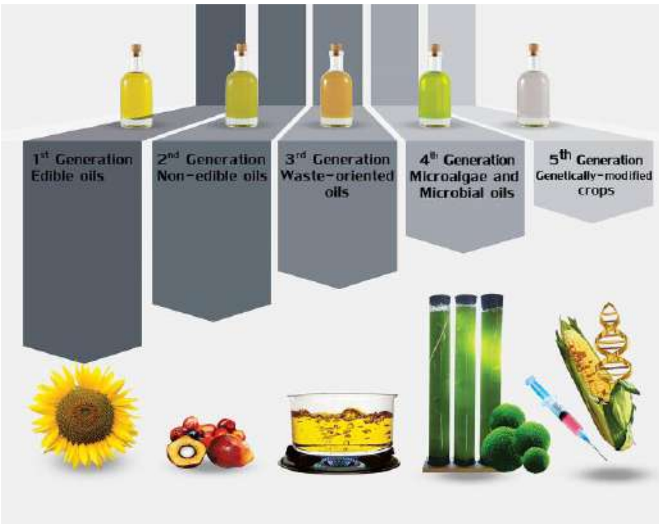


Fig. 1. Biodiesel classification based on feedstock.

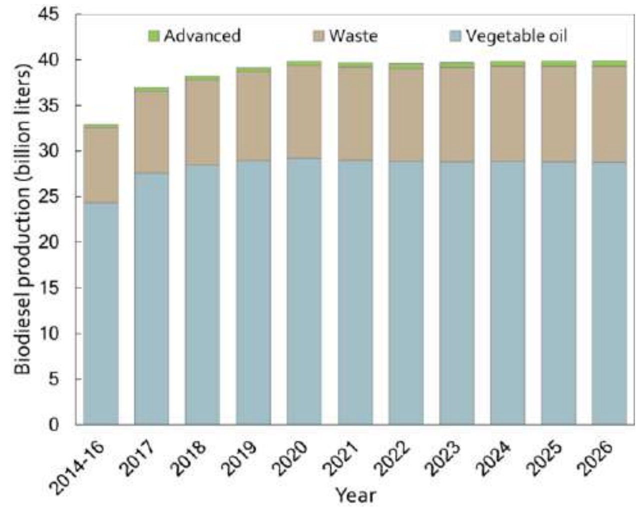


Fig. 2. Feedstock contribution to global biodiesel production (OECD/FAO, 2019).

production for land and water resources. Despite this unfavorable competition and the introduction of second- and third-generation feedstocks to address the challenge, edible oils, oily vegetables, and crops still retain the highest share in biodiesel production (**Fig. 2**).

Efforts have been made to increase the yield of oily vegetables and crops. Traditionally, chemical species (e.g., fertilizers, herbicides, and pesticides) have been used effectively to improve crop yield (Mirbakhsh, 2023). However, applying chemical species is not sustainable because of their environmental and health impacts (Vijayakumar et al., 2023). Alternatively, innovative nanotechnology-based approaches have been developed to maximize the feedstock yield (farm output yield) using minimal resources. **Figure 3** depicts the potential applications of nanotechnology in agriculture.

Generally, the insertion of nanoscale materials into plants can provide the programmed, time-controlled release of agrochemicals (e.g., fertilizers, pesticides, and herbicides) as well as target-specific delivery of biomolecules (e.g., nucleotides, proteins, and activators) (Fraceto et al., 2016; Sohrabi et al., 2023). The application of nanotechnology in the production of oil crops fits into two major categories: nanofertilizers (Liu and Lal, 2014; Yang et al., 2023) and nanopesticides (Guan et al., 2010). This section presents a comprehensive examination of the advantages and disadvantages associated with using nanoparticles in agriculture. Understanding these factors is crucial for assessing the sustainability of nanoparticle applications in the production of biodiesel feedstock.

2.1.1. Nanofertilizers

Nanoparticles can significantly improve the agronomic and economic feasibility of vegetable oil feedstocks by acting as fertilizers or fertilizer enhancers (Liu and Lal, 2014; Mahapatra et al., 2022). In the former application, nanomaterials supply one or more nutrients a crop needs to promote its growth and yield (Dewdar et al., 2018). Compared to traditional fertilizers, some nanofertilizers are safe for beneficial soil microbiota and provide higher nutrient availability and lower nutrient run-off (Pandey, 2018; Kalwani et al., 2022). A summary of the effects of some macro/micronutrient nanofertilizers used to produce vegetable oil feedstocks is shown in **Table 2**.

The second group of nanofertilizers (i.e., nanomaterial-enhanced fertilizers) contains engineered nanomaterials that can increase plant nutrient consumption (i.e., absorption, uptake, transport, and penetration) efficiency (**Fig. 4**) (Liu and Lal, 2015). These nanomaterials do not directly supply crops with nutrients while improving crop productivity, especially when co-applied with traditional fertilizers (Elsayed et al., 2022; Kumar et al., 2022a). The action mechanisms of the second nanofertilizer group include (i) binding to chemical fertilizers and facilitating their translocation into various plant organs, (ii) circulating (i.e., up, down, and radial movements) within the plant through symplastic or apoplastic pathways, (iii) modulating the absorption of soil chemical and microbial contents by plant, and (iv) penetrating plant cells through pore formation, endocytosis, plasmodesmata, and carrier proteins (**Fig. 4**).

Applying nanoparticles (e.g., cupric oxide, iron oxide, and zinc oxide) may not be eco-friendly (Azam et al., 2022). Nanoparticles may complicate the soil ecosystem process (e.g., the carbon or nitrogen cycle) by suppressing the growth of nematode *Caenorhabditis elegans* and earthworm *Eisenia fetida*, decreasing the diversity and population of the soil microbial community, and poisoning higher trophic groups in the soil food web (e.g., grazers) (Rashid et al., 2017). Nanomaterials may also render phytotoxic effects based on nature, size, dose, and exposure time. For example, cupric oxide increases the rate of organic matter decomposition in the soil while inhibiting pollen germination, seed germination, and root growth of various *Arabidopsis thaliana* ecotypes (probably because of the production of reactive oxygen species (ROS)) (Guerriero and Cai, 2018). A high concentration of nanoparticles, especially ≥20 nm, in the root zone can decrease crop production yield by interfering with the uptake of nutrients and water (Usman et al., 2020).

Besides soil nutrients and availability, crop yield is affected by soil pollution. Nanomaterials can extensively trap many soil and groundwater contaminants because of the large specific surface area (including microporous channels with network structures) and the high reactivity (Yang et al., 2016). Favorable engineered nanoparticles intended for *in-situ* remediation must show less toxicity, appropriate mobility within porous media, and sufficient lifetime and reactivity (Chen et al., 2017). Based on these criteria, nanoscale elemental or zero-valent metals (iron, nickel, and palladium) are considered promising adsorbents of transitional metals (arsenic and chromium) and persistent organic pollutants (Cecchin et al., 2017; Babu et al., 2022). Fe-based nanoparticles are more economically feasible (simple removal and recyclability) for water remediation due to their magnetic properties (Cundy et al., 2008). For soil remediation, iron-based nanoparticles (e.g., zero-valent iron (ZVI) nanoparticles) offer the unique advantage of being soil deliverable, while they are highly reactive to many plant-detrimental contaminants (heavy metals) (Zhao et al., 2016b). The typical modification methods of ZVI nanoparticles include their immobilization onto suitable supports, surface modification, and admixtures of compatible metals with ZVI nanoparticles (**Fig. 5**) (Xue et al., 2018).

Figure 6 presents a schematic diagram summarizing the preparation and application of stabilized ZVI nanoparticles for *in-situ* contaminated soil and groundwater remediations.

Another iron-based nanoparticle is iron sulfide, which is chalcophilic in nature. This nanoparticle can remediate heavy metals (arsenic, cadmium, and chromium) due to its ability to donate electrons (releasing iron^{2+} and

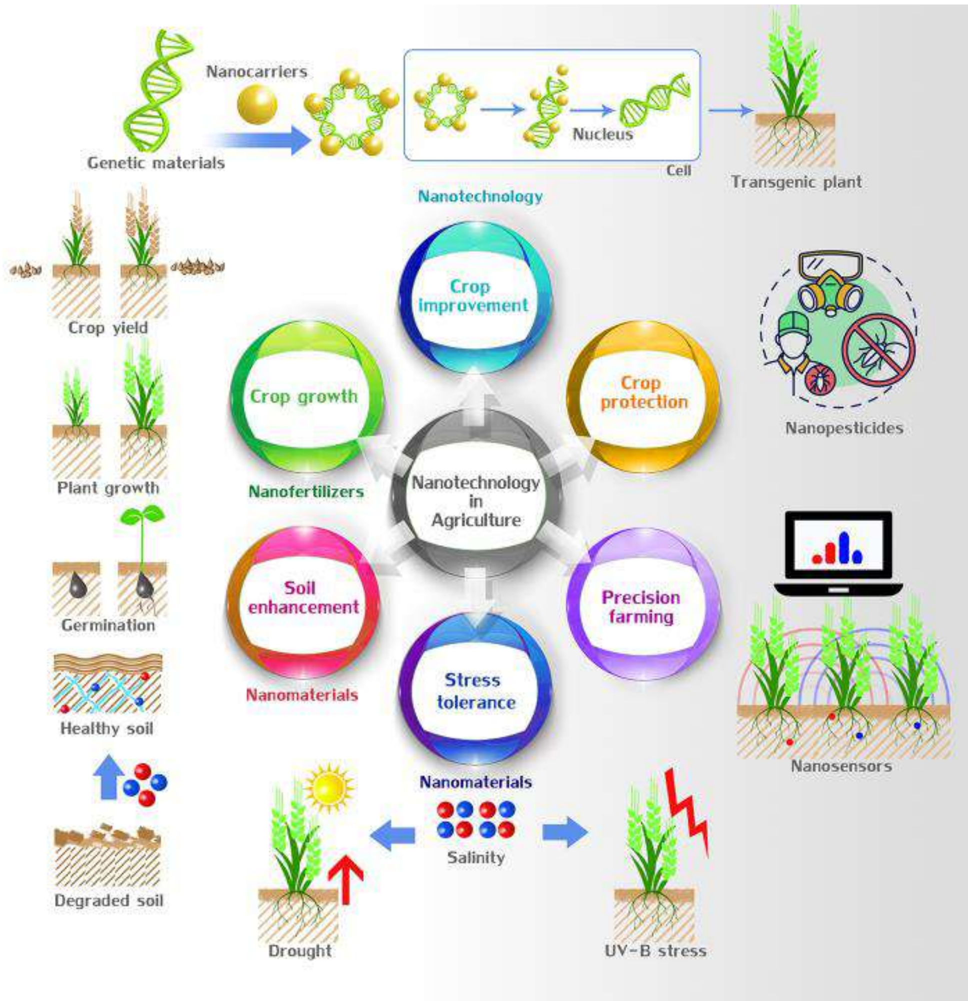


Fig. 3. The potential applications of nanotechnology in agriculture. Controlled released nanofertilizers increase crop growth, yield, and productivity through efficiently protecting the crop, allowing gene transfer (nano-based target delivery approach), contributing to precision farming *via* nanosensors and computerized controls platform, promoting plant stress tolerance, and soil enhancement. Adapted and redrawn from Shang et al. (2019).

sulfur^{2-}). The immobilization of humic acid through electrostatic adsorption and organic complexation further enriches surface functional groups on iron(ii) sulfide nanoparticles, while carboxymethyl cellulose is used as a stabilizer to prevent the agglomeration of the nanoparticles. The novel composite (carboxymethyl cellulose-iron(ii) sulfide@ humic acid) can then efficiently remediate chromium(VI) from contaminated soil (**Fig. 7**) (Tan et al., 2020).

Despite significant agricultural productivity improvements, applying iron-based nanoparticles may be challenging because of the loss of reactivity with aging (**Fig. 8**). During *in-situ* remediation of contaminated zones, the clustering tendency of ZVI nanoparticles reduces their mobility through soil pores by accelerating the deposition of soil particles (Cecchin et al., 2017).

ZVI nanoparticles can be cytotoxic against some microbial species through iron^{2+} release, ROS generation, oxidative stress, and subsequent cell membrane disruption (Lefevre et al., 2016). Therefore, applying ZVI nanoparticles may knock out some important functional microorganisms for biogeochemical processes. At high concentrations, ZVI nanoparticles may decrease growth and aspiration in some plants by reducing the root adsorption efficiency of nutrients and water. This could be attributed to the accumulation of ZVI nanoparticles or iron^{3+} (the oxidation product of ZVI nanoparticles) on roots and/or the internalization of ZVI nanoparticles into root epidermal cells (Jiang et al., 2018). In addition, ZVI nanoparticles may cause oxygen deficiency and iron^{2+}-induced reductive effects in soils, negatively affecting plant growth (Jiang et al., 2018). More specifically, oxygen depletion affects both root growth/survival and the rhizosphere microbial community (Lefevre et al., 2016). Notably, the induction of oxidative stress by nanoparticles could be caused by the overexpression of ascorbate peroxidase, catalases, and superoxide dismutase when they enter plant tissues (Ding et al., 2017).

The application of nanotechnology for soil remediation can be combined with bioremediation to overcome the challenges mentioned (Cecchin et al., 2017). The developed technique, known as nanobioremediation, uses microbial or plant-derived nanoparticles (Yadav et al., 2017). The first step of nanobioremediation involves the application of biological nanoparticles at a concentration that is enough to bring the pollutants to an appropriate level for the biodegradation process (Usman et al., 2020). In the second step, microbial or phyto bioremediation ability is exploited to degrade various organic or inorganic pollutants (Hamedi et al., 2015). Through this strategy, the economic and/or environmental feasibilities of both mentioned remediation techniques are substantially improved.

An alternative to nanoscale elemental or zero-valent metals in agriculture is carbon-based nanomaterials (CNM) such as carbon nanotubes (CNTs), fullerenes, carbon nanodots, carbon nanofibers, graphene oxides, carbon nanohorns, and carbon nano-dots (Aacharya and Chhipa, 2020). **Figure 9** shows some CNMs with a growth-promoting effect on plants. These compounds have been extensively applied as plant growth regulators, pest detection and control agents, pesticide sorbents, and nutrient carriers in agriculture (**Table 3**). The engineering of nanoparticles could further

Table 2.
A summary of the effects of some macro/micronutrient nanofertilizers used to produce vegetable oil feedstocks.

Nanoparticle	Size (nm)	Concentration (ppm)	Nutrient provided	Investigated plant oil feedstock		Reference
				Species	Effect	
Apatite	18.9–20.3	21.8	Micro-nutrient (Iron)	Soybean	Increased the growth rate (32.6%) and seed yield (20.4%) compared to chemical fertilizer, i.e., Calcium dihydrogen phosphate	Liu and Lal (2014)
Calcium carbonate	20–80	160	Macro-nutrient (Calcium)	Peanut	Increased nutrient content in the roots and shoots	Liu et al. (2005)
Copper dioxide	<50	10	Micro-nutrient (Copper)	Corn	Increased plant growth by 51%	Adhikari et al. (2016)
Iron chelates	-	-	-	Soybean	Significantly increased oleic acid when co-applied with farmyard manure	Mohammadi (2015)
Iron-humic	-	32.6–57.8	Micro-nutrient (Iron)	Soybean	- Continuous long-term uptake of Fe - Increased shoot yield.	Cieschi et al. (2019)
Iron oxide	-	500	Micro-nutrient (Iron)	Soybean	48% Increased grain yield by 48%	Sheykhbaglou et al. (2010)
NPK*-loaded chitosan	300–750	10–50	Macro-nutrients (NPK)	Coffee	Increased plant height, leaf number, and leaf area	Ha et al. (2019)
Super-paramagnetic iron oxide	20	30–60	Micro-nutrient (Iron)	Soybean	Increased chlorophyll levels	Ghafariyan et al. (2013)
Zinc oxide	20	80	Micro-nutrient (Zinc)	Corn	Increased germination (17%), root length (25%), and dry biomass yield (12%)	Esper Neto et al. (2020)
Zinc oxide	<100	-	Micro-nutrient (Zinc)	Corn	Enhanced growth	Adhikari et al. (2015)
Zinc oxide	25	1,000	Micro-nutrient (Zinc)	Peanut	Increased yield per plant (by 34%) compared to chelated bulk Zinc sulfate	Prasad et al. (2012)
Zinc oxide	-	40–400	Micro-nutrient (Zinc)	Soybean	Increased seed yields up to 160 mg/kg	Yusefi-Tanha et al. (2020)
Zinc or Iron	-	2000	Micro-nutrient (Iron or Zinc)	Corn	Increased biomass, crude protein, and soluble carbohydrate concentration compared to chemical fertilizers counterparts	Sharifi et al. (2016)

* Nitrogen, phosphorous, and potassium.

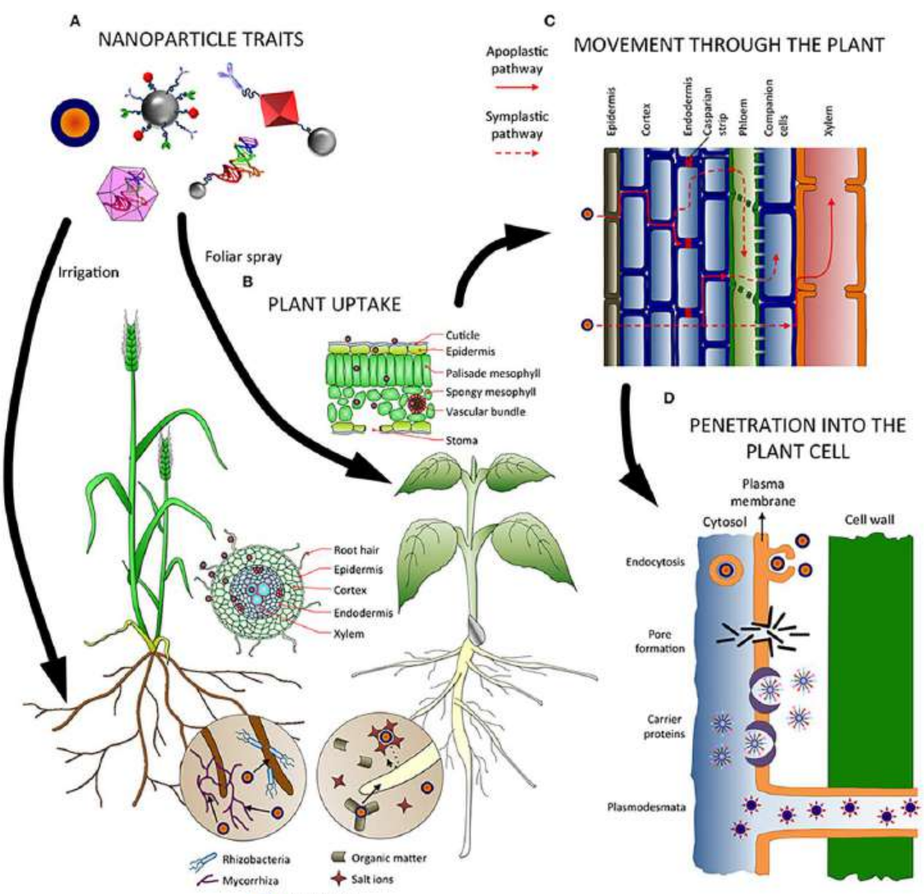


Fig. 4. The Mechanisms of nanoparticle absorption, uptake, transport, and penetration in plants. **(A)** Nanoparticle traits, **(B)** nanoparticle uptake by the plant, **(C)** nanoparticle movement within the plant, and **(D)** nanoparticle penetration into plant cells (Pérez-de-Luque, 2017).

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

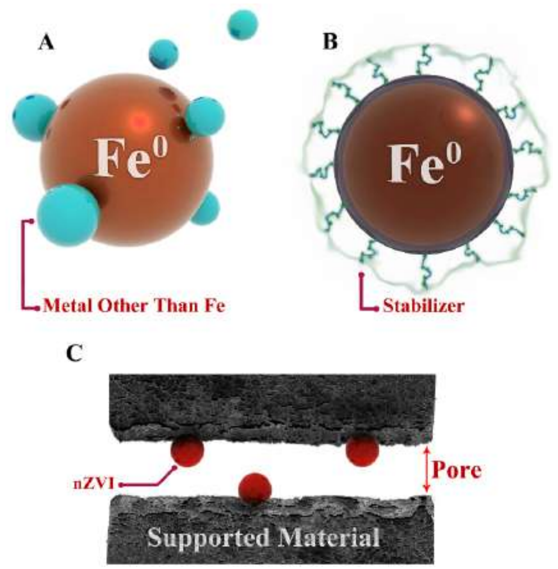


Fig. 5. A schematic presentation of different ZVI nanoparticle modification methods. **(A)** Metal doping, **(B)** surface modification, and **(C)** support deposition. Adapted and redrawn from Xue et al. (2018).

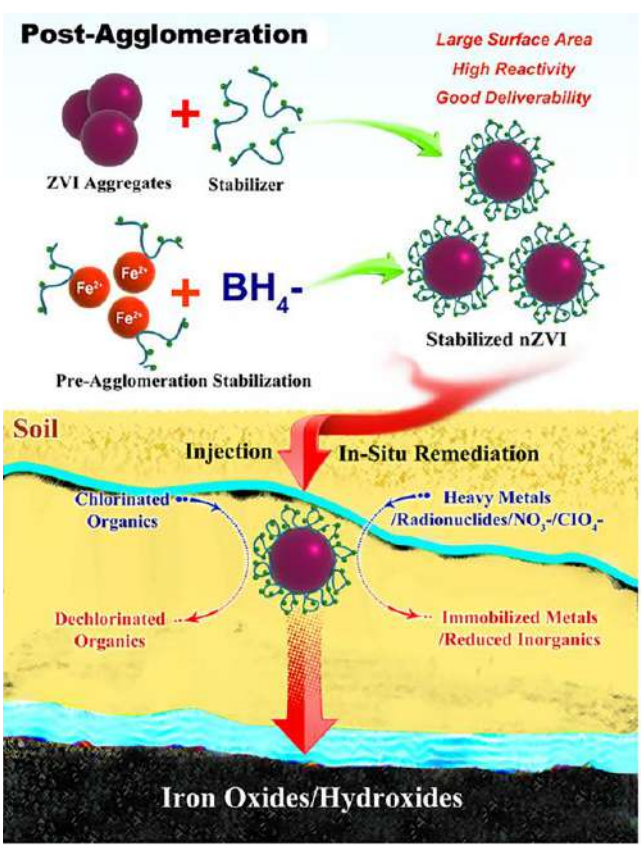


Fig. 6. A Schematic diagram on synthesis, application, transport, and fate of stabilized ZVI nanoparticles. Adapted and redrawn from Zhao et al. (2016b).

modify them for better performance. On this basis, functionalized nanocarbons show facilitated transportation into plant cells compared to nonfunctionalized

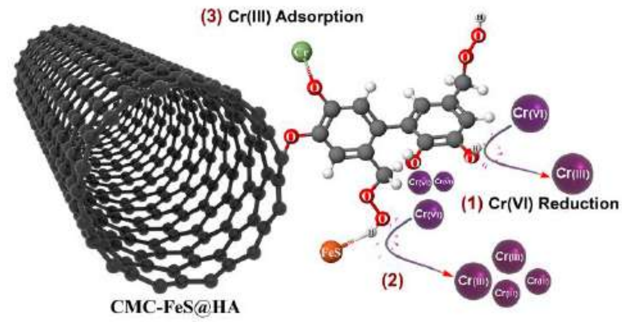


Fig. 7. The mechanisms for reducing chromium(VI) toxicity by composite materials. **(1)** chromium(VI) ion is adsorbed on the oxygen-containing functional groups of humic acid and is reduced. **(2)** chromium(VI) ion is rapidly reduced into chromium(III) ion following its reaction with iron(ii) sulfide . **(3)** Small amount of chromium(III) is adsorbed by humic acid. Adapted and redrawn from Tan et al. (2020).

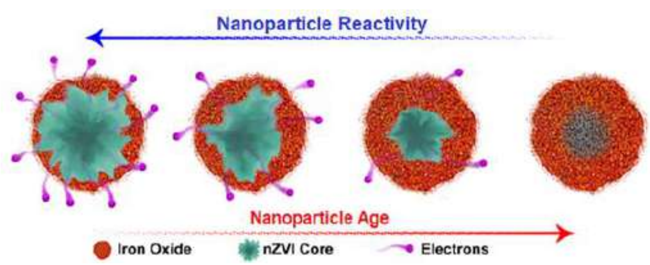


Fig. 8. Effect of aging on the reactivity of ZVI nanoparticles. Adapted and redrawn from Cecchin et al. (2017).

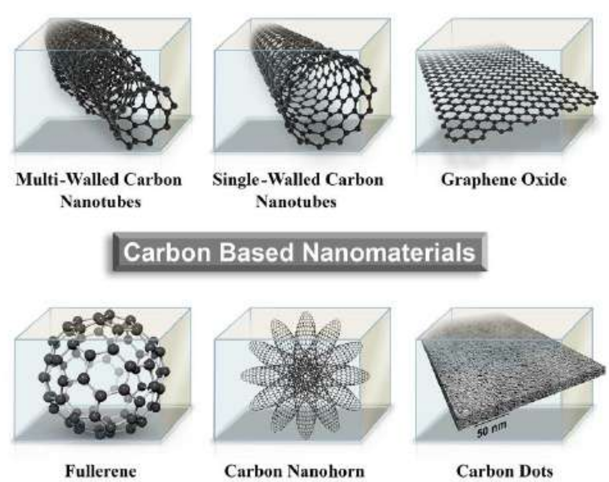


Fig. 9. Different carbon-based nanomaterials used in agriculture as plant growth promoters.

nanocarbons. Like water-soluble nanoparticles, the growth-stimulating effects of functionalized nanocarbons are due to their ability to enhance water conduction in plants by reaching the tracheal elements of xylem vessels (Singh et al., 2018).

According to **Table 3**, the effects of CNMs on agriculture yield significantly depend on plant species, environmental stresses (e.g., drought or soil contaminants), and the type and amount of the incorporated CNMs.

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

Table 3.
An overview of all the studies involving carbon-based nanomaterials for cultivating plant oils.**

Investigated plant oil feedstock	Nanoparticle	Size (nm)	Concentration	Domain of effect		Reference
				Quantity	Quality	
Bitter melon	Fullerol	1.5–5	4.7–47.2 nM	✓*	✓	Kole et al. (2013)
Cannabis sativa	MWCNTs[1]	100	10–50 mg/L	✓	✗	Oloumi et al. (2018)
Corn/Maize	Fullerenol	~138	50–400 mg/L	-	✓	Liu et al. (2016a)
	MWCNTs	15–40	25–200 mg/L	✓	✓	Lahiani et al. (2013)
	Water-soluble CNTs-COOH	10–20	20–50 mg/L	✓	✓	Srivastava and Rao (2014)
	Water-soluble carbon nano-dots	~3	1–2 g/L	✗	✗	Chen et al. (2016)
	MWCNTs	-	50 µg/mL	✓	✗/✓	Lahiani et al. (2017)
	Pristine MWCNTs	6–9	5–60 mg/L	✗/✓	-	Tiwari et al. (2014)
	Sulfonated graphene	-	50 mg/kg soil	-	✗/✓	Ren et al. (2018)
	SWCNT[2]	1–2	20 mg/L	No	No	Yan et al. (2013)
	MWCNTs	-	10–50 mg/L	✓	-	Zhai et al. (2015)
Palm	MWCNTs	110–170	0.05 mg/L	✓	✓	Taha et al. (2016)
Pumpkin	Fluorescent carbon dots	4	100–400 mg/L	-	✓	Qian et al. (2018)
Rapeseed	Graphene oxide	-	25–50 mg/L	✓	-	Cheng et al. (2016)
	Fullerol	-	1–100 mg/L	✓	✓	Xiong et al. (2018)
	MWCNTs	10–150	10-100 mg/L	No	No	Larue et al. (2012)
	MWCNTs	100	10–50 mg/L	✓	✗	Oloumi et al. (2018)
Soybean	MWCNTs	15–40	25–200 mg/L	✓	✓	Lahiani et al. (2013)
	MWCNTs	-	50 µg/mL	✓	✗/✓	Lahiani et al. (2017)
	MWCNTs	-	10–50 mg/L	✗	-	Zhai et al. (2015)
Squash	MWCNTs	13–16	1,000 mg/L	✗	-	Stampoulis et al. (2009)
	MWCNTs	5–15	125–1,000 µg/mL	✗	✗	Hatami (2017)
Squash	$Carbon_{60}$ fullerenes	-	~1.7 g/kg soil	✗/✓	-	Kelsey and White (2013)
Sunflower	MWCNTs		10–50 mg/L	✓	✗	Oloumi et al. (2018)
Tobacco	Carbon nanoparticles	-	25–25 mg/pot	✓	✓	Liang et al. (2013)
	Carboxyfullerence	100–200	10–144 mg/L	✗	✗	Liu et al. (2013)

[1] Multi-wall carbon nanotubes.
[2] Single-wall carbon nanotubes.
*✓: positive effect ✗: negative effect ✗/✓: both positive and negative effect No: no effect
** Adapted from Verma et al. (2019).

These factors play critical roles in CNM-induced phytotoxicity at anatomical, morphological, physiological, cellular, and genetic levels (Verma et al., 2019). More specifically, mixed effects of the CNMs' exposure on plants ranging from an increase in vegetative growth and yield of fruit/seed at lower concentrations of CNMs to the progressive decrease in these observations at higher concentrations of CNMs, have been documented (**Table 3**). In general, at lower concentrations, CNMs are effective in enhancing (i.e., water uptake, water transport, seed germination, nitrogenase, photosystem, and antioxidant activities), activating (i.e., water channels proteins), and promoting (i.e., nutrition absorption), but all these beneficiary effects could change when CNM concentration is raised. Unlike *in-vitro* studies, the chronic phytotoxicity of CNMs has not been extensively examined by field studies (Mukherjee et al., 2016). It should be noted that soil physiological properties (e.g., soil components) modulate the toxicity of the incorporated CNM by affecting, for example, its reactivity and solubility (Mukherjee et al., 2016). This behavior further complicates the mechanistic understanding of cellular interactions between CNM and plants. Moreover, little is known about the effects of environmental factors on CNMs' stability, the release of their metals moiety, and the leach of adsorbed contaminants from CNMs (Mukherjee et al., 2016). Another concern about CNM fate is its unknown potential for bioaccumulation and/or biomagnification (Sangeetha et al., 2017). In light of these, future research should encompass the adverse impacts of nanomaterials on plants. Those impacts can be classified into different categories, nanomaterial phytotoxicity, reducing germination rate of seeds, decreasing fresh and dry biomass and length of roots and shoots, altering photosynthesis process, enhancing chromatin condensation, increasing deoxyribonucleic acid (DNA) damage, reducing the transpiration rate, enhancing lipid peroxidation, up-and down-regulation of various stress-related genes, and inducing plant cell apoptosis (Tripathi et al., 2017).

By consuming plant materials contaminated by nanoparticles (e.g., cadmium, copper, iron, manganese, nickel, lead, and zinc) by animals and humans, the contamination could be further biomagnified throughout the food chain. The high reactivity and transportability of nanoparticles also raise safety concerns for workers in direct contact with the production and

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

application of these compounds (Iavicoli et al., 2017). More specifically, nanoparticles could be absorbed at different rates, depending on their types, into human (and animal) bodies through inhalation, ingestion, and skin contact. They could mainly interact with cells through adhesion, endocytosis, semi-endocytosis, and penetration. The greater surface area of nanoparticles elicits a higher toxic dose response than similar concentrations of their bulk counterparts. For instance, exposure to leaked titanium dioxide nanoparticles in animals and humans induces tissue degradation and organ injury mainly through oxidative stress, apoptosis, and necrosis. Excessive inflammation because of the high amount of biomolecules oxidized by nanoparticles and ROS may further induce aging, cancer, and other diseases (Ranjan et al., 2019).

The concentration of nanoparticles could play a significant role in their toxicity level. In a study, the toxicity of different concentrations of iron oxide nanoparticles on an animal model (i.e., zebrafish) was visualized by using a fluorescent dye (Congo red) conjugated with the nanoparticles. As shown in **Figure 10**, magnetic nanoparticles (i.e., Congo red@iron(II, III) oxide (Fe_3O_4) conjugates) exerted more toxicity on zebrafish larvae by increasing their concentration and resulting in the delay in hatching cycles at the concentration of 100 µg/m and mortality at concentrations exceeding 200 µg/mL (Jurewicz et al., 2020).

The level of nanoparticle toxicity may depend on the existence and type of surface coatings (i.e., ligands). Zheng et al. (2018) used the transcriptome sequencing technique and PCR to study the impact of magnetic nanoparticles (Fe_3O_4) coatings on adult zebrafish (*Danio rerio*). Compared to the naked nanoparticles, the fish exposure (7 d) to the starch-coated ones inflicted lower gill toxicity but more significant liver damage. This was due to higher bioaccumulation of positively charged naked Fe_3O_4 nanoparticles in gill cells with negatively charged surfaces. In contrast, starch-coated Fe_3O_4 nanoparticles had smaller sizes and showed a steric hindrance, preventing their attachment on collector surfaces in fish body. However, the very same property made the coated magnetic nanoparticles more transportable, leading to their higher accumulation in the liver. **Figure 11** illustrates the differentially expressed gene profiles in the gill and liver tissues of fish exposed to magnetic nanoparticles.

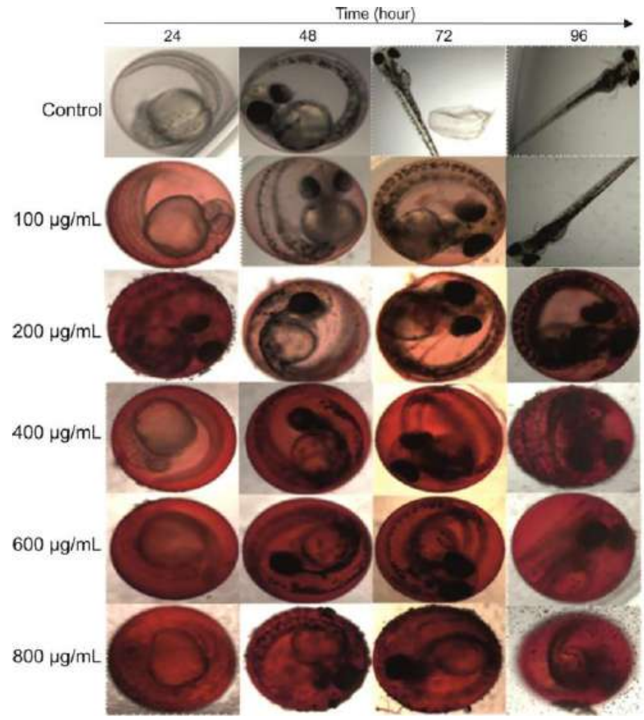


Fig. 10. Different intervals of Congo red@ Fe_3O_4 internalization into zebrafish embryos up to 96 h (Jurewicz et al., 2020). With Permission from the American Chemical Society. Copyright© 2020.

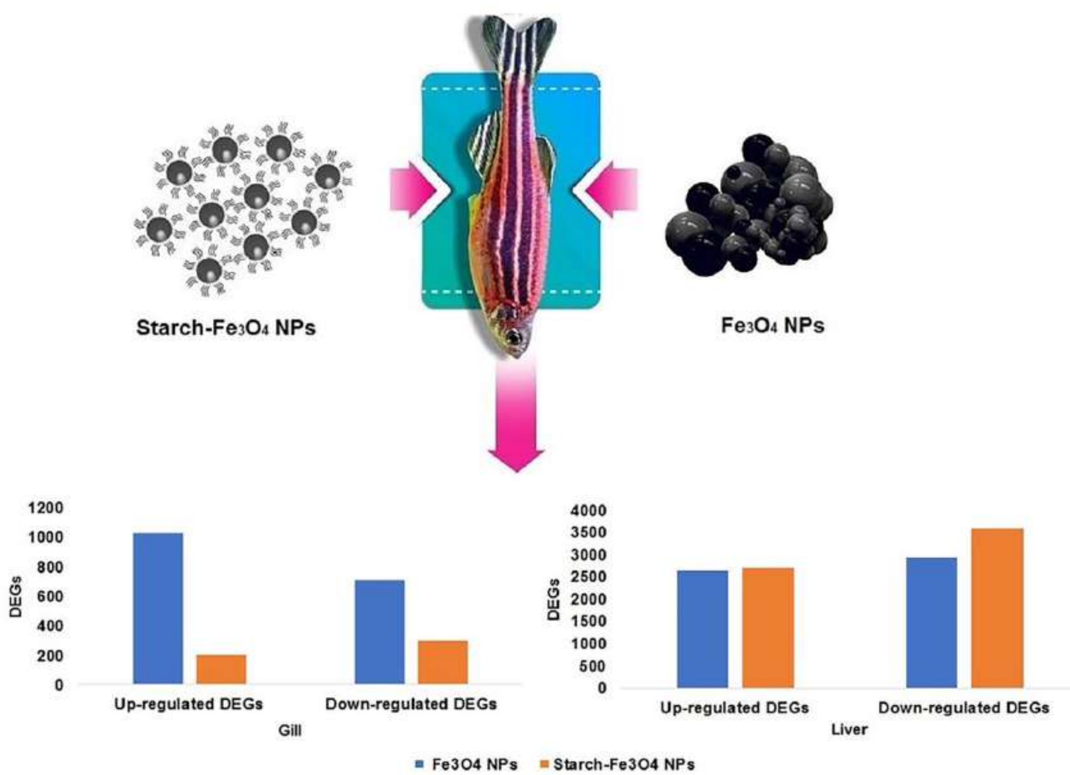


Fig. 11. Schematic diagram showing differently expressed gene profiles in the gill and liver tissues of fish exposed to magnetic nanoparticles, *i.e.*, naked and starch-coated Fe_3O_4 nanoparticles. Data from Zheng et al. (2018).

Figure 12 shows the effect of uncoated, polyvinylpyrrolidone-coated, or citrated-coated silver nanoparticles on macrophages and HT29 epithelial cells. Uncoated and coated-Ag nanoparticles triggered oxidative stress and inflammatory responses, respectively (Nguyen et al., 2013). Accordingly, coated-silver nanoparticles resulted in cell enlargement and elongation, whereas uncoated ones induced cell shrinkage (**Fig. 12**). These findings implied that the absence of coating could be more toxic. However, the exact level of toxicity of any nanoparticles would significantly depend on their size and the nature of the coated ligand used and hence, should be investigated case by case. For instance, the application of toxic ligands (*e.g.,* cetyltrimethylammonium bromide, poly(diallyldimethylammonium) chloride, bionic, and oleate) in nanoparticle functionalization may render more toxicity effects compared to naked nanoparticles (Bozich et al., 2014). On the contrary, citrate-coated nanoparticles induced lower cytotoxicity than polyvinylpyrrolidone-coated ones (Nguyen et al., 2013). This could be attributed to their difference in the extent they prevent silver nanoparticles from leaching.

In addition to bioavailability, coatings, through their surface charge, could also influence the cytotoxicity of nanoparticles. In fact, the surface charge of the coating is more significant in terms of cytotoxicity, whereas its composition is a significant factor from the ROS generation point of view. In this context, cadmium selenide/zinc sulfide core/shell nanoparticles with positively charged coatings (e.g., polyethylenimine or cysteamine) were absorbed more by cells (i.e., HaCaT keratinocytes) compared to their counterparts with negatively charged coatings (e.g., dihydrolipoic acid or glutathione) (Zheng et al., 2017).

The shape of nanoparticles is another determinant of their toxicity. For example, fiber-like nanoparticles show poor miscibility in application media and, hence, could release into the air. Following their release, these nanoparticles could be inhaled and cause blood contamination by directly entering the bloodstream from the lungs, ultimately reaching all other body organs. Another contributing factor to the health impacts of nanoparticles is their size. More specifically, the nano-sized dimension of these particles

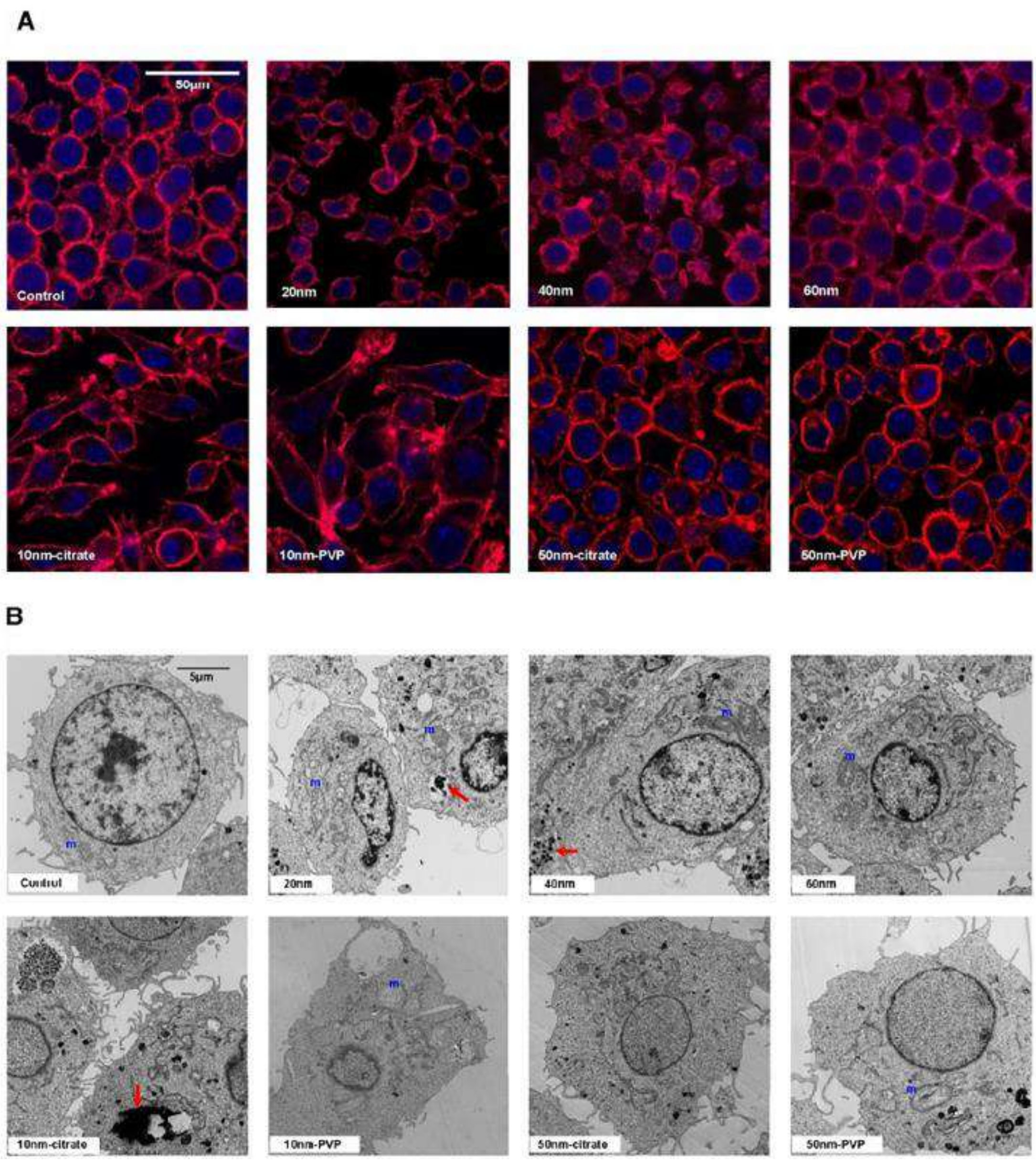


Fig. 12. Confocal micrographs **(A)** and TEM micrographs **(B)** of J774A.1 cells exposed to coated and uncoated silver nanoparticles for 24 h. Structures stained in pink and blue are for F-actin and nucleus, respectively. Arrows show the existence of intracellular silver nanoparticles, and “m” stands for mitochondrion (Nguyen et al., 2013).

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

allows them to reach various susceptible body parts, for example, the brain, *via* crossing the blood-brain barrier, a physical barrier their bulk-size counterpart cannot cross (Dehhaghi et al., 2019). Once inside the brain, nanoparticles could induce various neurodegeneration diseases, including Alzheimer's disease, amyotrophic lateral sclerosis, Huntington's disease, multiple sclerosis, and Parkinson's disease, potentially through rendering apoptosis, neuroinflammation, and neuronal cell loss (Dehhaghi et al., 2019). Therefore, it is crucial to carefully consider and engineer various aspects of nanoparticles before applying them in agriculture to ensure health and safety standards.

2.1.2. Nanopesticides

Conventional pesticides contain coarse particles and show less than 30% annihilation efficiencies against targeted pest species (Hayles et al., 2017; Rani et al., 2023) due to low biological activity, dispersibility, and stability (Zhang, 2018; Manzoor et al., 2023). These pesticides also have many side effects on the surrounding ecosystem and human health (**Fig. 13**).

compounds (Sun et al., 2019; Mubeen et al., 2023). Nanopesticides are categorized into (i) pesticides whose effective ingredients are nano-sized, usually in the form of a powder, nanodispersant, or microemulsion (Jiang et al., 2012), and (ii) those effective ingredients are in interaction with nanomaterials through encapsulation, entrapment, adsorption, and binding (**Fig. 14**) (Kumar et al., 2019). The designation aims of the second group of nanopesticides are to improve the performance of a conventional pesticide, reduce its release into the environment, and minimize the exposure of non-targeted species (Jindal et al., 2017; Pan et al., 2023). Through this strategy, nanoparticles can protect pesticide agents against degradation, leaching, photolysis, and volatilization while improving the delivery and bioavailability of water-insoluble active ingredients (Sun et al., 2019; Paz-Trejo et al., 2023).

Despite the mentioned advantages of nanopesticides, concerns with respect to their biosafety and long-term ecological and health effects, especially on the labor exposed to these compounds, have emerged (Iavicoli et al., 2017). For example, nanopesticides can be evaporated before

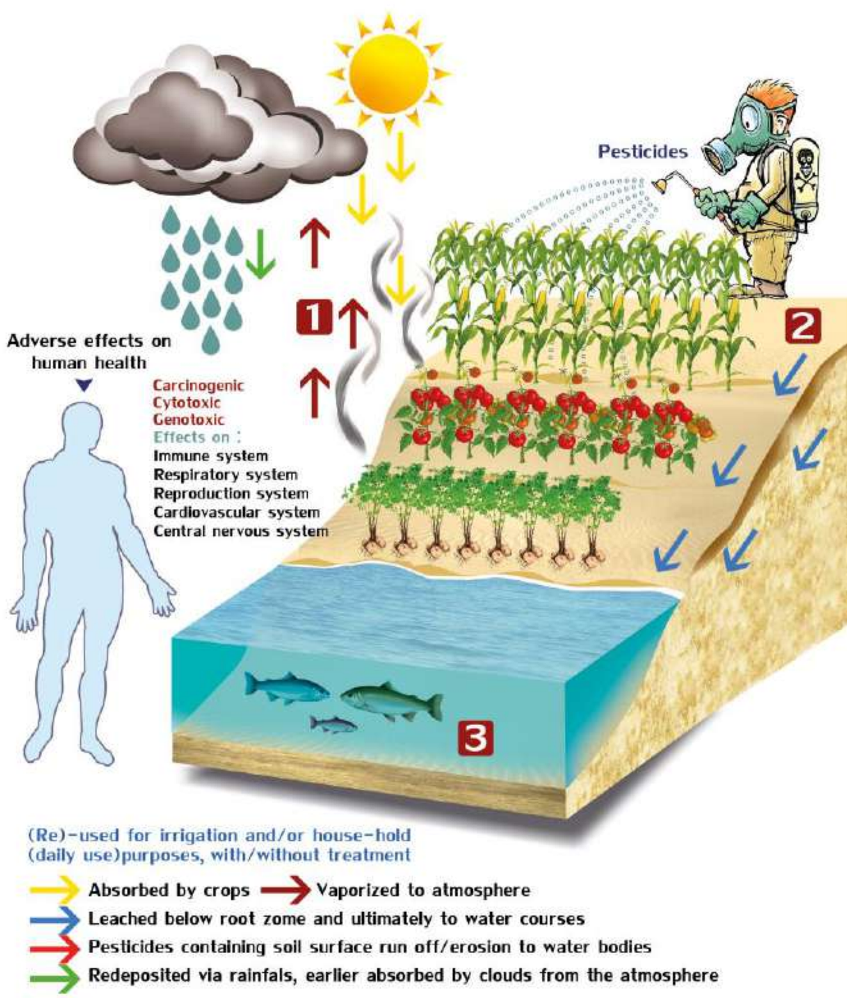


Fig. 13. Relocation and adverse side effects of conventional pesticides on the ecosystem, *i.e.*, **(1)** air, **(2)** land, and **(3)** water. Adapted from Liu et al. (2019).

The detrimental effects of conventional pesticides are generally persistent for a long time or could even be irreversible (Kah and Hofmann, 2014; Hennig et al., 2023). Therefore, novel plant protection methods against pests must be developed, among which nanopesticides are considered promising alternatives. Nanopesticides show higher mobility, solubility, dispersibility, durability, and leaf adhesion (Kah et al., 2013). Controlled release and favorable biocidal activities (even at low concentrations) are the other features of these

reaching the targeted-leaf surface when sprayed in tiny droplets (Kumar et al., 2019). Notably, most emulsifiable concentrates and microemulsions used in nanopesticides are polar solvents (*e.g.,* alcohols, benzenes, and ketones), some of which have high acute toxicity and easily find their way into animal and human bodies through contaminated farmlands and groundwater. Polar solvents are persistent and accumulate in the environment , which could widely cause acute poisoning and

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

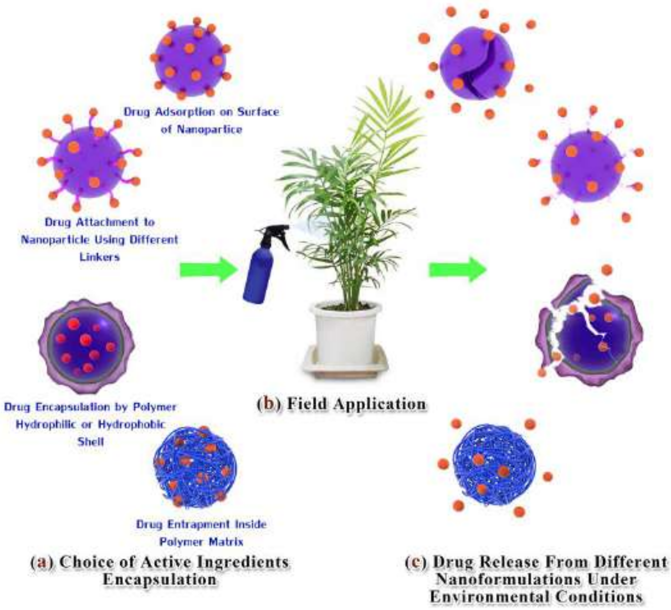


Fig. 14. Schematic presentation of different nanoformulations (synthesized through interactions between active ingredients and nanoparticles) and the release of active materials from them. Adapted and redrawn from Kumar et al. (2019).

even death of animals (Sun et al., 2019).

Finally, the potential, extent, and environmental effects of the combined toxicity of nanopesticides and nanofertilizers are still poorly studied. Therefore, the fate of these compounds must be extensively studied before their commercial applications. **Figure 15** illustrates the life-cycle assessment of nano-enabled products in agriculture (Iavicoli et al., 2017).

2.2. Microalgae oil

Microalgae with high lipid contents can be used as feedstock for third-generation biodiesel production. These organisms could deliver a high photosynthesis rate and growth rate (Nan et al., 2023; Sathya et al., 2023) even if cultivated on unproductive land using wastewater and saline water (Satpati et al., 2023; Vasistha et al., 2023). Microalgae do not require pesticides or herbicides (Chiaramonti et al., 2017) while tolerating high carbon dioxide, nitrogen oxides, sulfur oxides, and particulate matter concentrations (Imhoff et al., 2011). Regarding fuel properties (e.g., heating value, density, viscosity, and acid value), algal biodiesel is comparable to petrodiesel (Kings et al., 2017). Considering the advantages, algal oil could be regarded as a sustainable feedstock for biodiesel production if the two major elements jeopardizing its commercial feasibility (i.e., microalgal biomass cultivation and harvesting) are further improved.

2.2.1. Microalgae biomass cultivation

Direct use (as a micronutrient supplement) or indirect use (as a light scattering and absorption improver and antimicrobial agent) of nanoparticles can improve algae growth rate by improving growth-related physiological processes. **Figure 16** summarizes the performance of nanoparticles as micronutrient supplements for enhancing microalgae growth and lipid accumulation. Low nanoparticle doses (i.e., <100 mg/L) typically produce higher performance efficiencies during microalgae cultivation. Regarding performance time, the lower nanoparticle doses could improve lipid productivity, lipid percentage, and biomass yield. Unlike these performance indicators, higher nanoparticle doses could enhance the growth rate factor (i.e., 200–300 mg/L). Moreover, the larger nanoparticle size within the investigated range could significantly affect the performance indicators: lipid percentage and biomass yield.

Concerning their direct use, nanomaterials can enhance cell size and lipid accumulation in microalgae by exerting oxidative stress and stimulating rapid nutrient uptake (Kang et al., 2014). This approach allows ZVI nanoparticles to be used as micronutrient supplements to improve photosynthesis rate, growth rate, and lipid production and accumulation while reducing the requirements for organic carbon sources (Sarma et al., 2014). These effects may be attributed to the provision of a suitable source of iron (i.e., ZVI nanoparticle oxidation to iron^{2+}) (Pádrová et al., 2015). In a study, the growth and physiology of three key coastal marine microalgae (*Isochrysis galbana*, *Pavlova lutheri*, and *Tetraselmis suecica*) were not negatively affected in the medium containing ZVI nanoparticles. Unlike the control, abundant, fully formed (perfectly spherical) large storage lipid bodies were identified within microalgal cells using cellular micromorphological analysis by transmission electron microscopy (Kadar et al., 2012). Both the diameter and number of oil droplets were increased in *I. galbana* in the presence of ZVI nanoparticles. Despite being healthy, all the mentioned microalgae developed a mesh of gel-like substances around their plasma membrane (Kadar et al., 2012). As ZVI nanoparticle is more bioavailable, significantly lower amounts were required to support algal growth than Fe-chelated ethylenediaminetetraacetic acid (the bulk analog). The higher bioavailability of ZVI nanoparticles could be attributed to their ability to be internalized by endocytosis and their facilitated penetration into the cytosol through higher interaction with the microalgae cell surface (Ševců et al., 2011). In another study, lipid accumulation was strongly enhanced in two eustigmatophycean algae (*Trachydiscus minutus*, *Nannochloropsis limnetica*) and four green algae (*Raphidocelis subcapitata*, *Parachlorella kessleri*, *Dunaliella salina*, *Desmodesmus subspicatus*) following the addition of 5.1 mg/L ZVI nanoparticle in Zehnder culture medium. ZVI nanoparticles could also increase the proportion of polyunsaturated fatty acids in the resultant algal lipid (Pádrová et al., 2015). This feature could be regarded as favorable in cold climates by enhancing the cold flow properties of the prospective biodiesel, while it could be considered unfavorable in hot climates by adversely influencing biodiesel's oxidative stability (Talebi et al., 2013).

Nanoparticles with bactericidal activities could be exploited as micronutrient elements while preventing the overgrowth of contaminating bacteria, a significant concern during commercial cultivation of mixotrophic microalgae. On this basis, magnesium aminoclay nanoparticles (concentration, 0.01–0.1 g/L) were successfully applied in *Chlorella* sp. KR-1 to suppress the growth of contaminating bacteria (Kim et al., 2016). Interestingly, lipid production was also improved by 25% compared to the control, reaching ~410 mg fatty acid methyl ester /L/d (Kim et al., 2016).

Regarding their indirect use, nanoparticles can enhance photosynthetic activity (i.e., by inducing the higher formation of carotenoid and chlorophyll pigment) (Eroglu et al., 2013) and overactivate key metabolic enzymes (e.g., nitrate reductase, glutamate-pyruvate transaminase, glutamate dehydrogenase, and glutamine synthase) (Mishra et al., 2014). Limited light penetration in high-density cultures is a major constraint of commercial microalgae cultivation. Nanoparticles can provide effective ways to mitigate the adverse effect of uneven light distribution on microalgae growth, especially in photobioreactors that require a longer light path length (Wang et al., 2022; Xiao et al., 2022). Using this capability, light penetrability into microalgae suspension can be facilitated by doping nanoparticles within planar waveguide modules that uniformly dilute and redistribute the intense incident light (Sun et al., 2018). Some advantages of planar waveguide modules doped with nanoparticles include low cost, long lifespan, high luminance uniformity, and flexibility for cutting into any size with no need for secondary processing. Sun et al. (2016) exploited nanoscale organosilicon-particle-embedded planar waveguide modules to cultivate microalgae *Nannochloropsis oculate* in a lab-scale open raceway pond. Compared to the bare open raceway pond, remarkable enhancements in both biomass and lipid yields were achieved because of a significant increase in light distribution within the microalgal culture. Upon encountering the nanoscale organosilicone particles, organosilicon-particle-embedded planar waveguide modules scatter the incident light irradiated into the planar waveguide from its edge and transmit it forward within it (**Fig. 17**).

In another study, the light scattering effect of silica nanoparticles led to a uniform distribution of light within a reactor during the photosynthetic

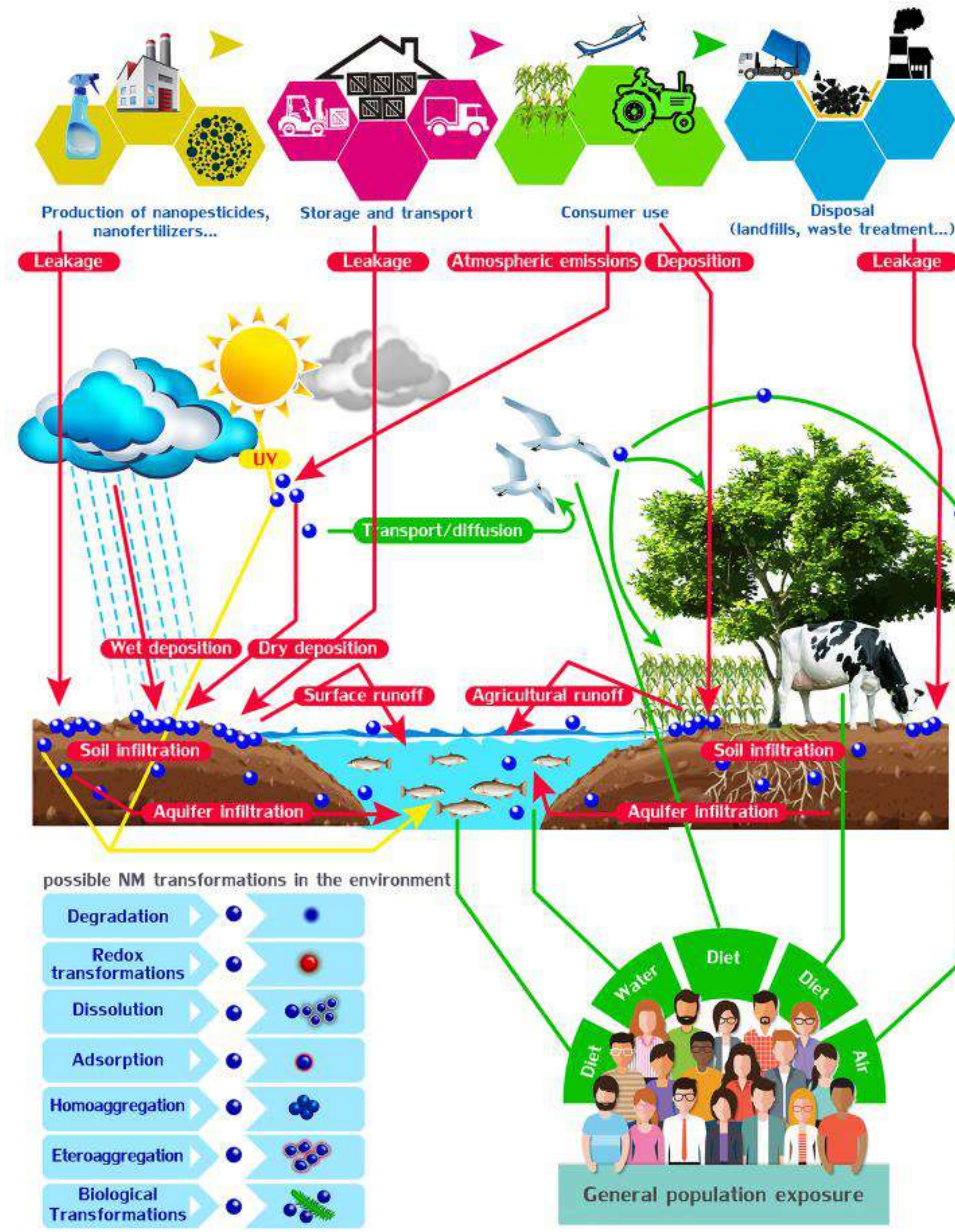


Fig. 15. Life-cycle of nano-enabled products used in agriculture. Adapted from Iavicoli et al. (2017).

process while promoting the growth rate of microalgal cells (Giannelli and Torzillo, 2012). Nanoparticles can also enhance light absorption in microalgal culture and subsequently increase both pigment and biomass production (Aratboni et al., 2023). For example, blue light absorption in microalgal cultures can selectively be improved by applying plasmonic filters made of silver nanoparticles with polymer films (Estime et al., 2015). Besides light, nanoparticles can increase the absorption rate and efficiency of available carbon dioxide, further supporting photosynthesis in microalgae (Li et al., 2022; Yang et al., 2022a). In this context, both the growth rate and fatty acid methyl ester productivity of chemoautotrophic microalgae could be improved (Jeon et al., 2017).

Despite the mentioned favorable properties, the steadily increasing application of engineered metal-based nanoparticles in microalgae cultivation has caused growing concerns about their fate in aquatic environments. When entering aquatic compartments, nanoparticles will be exposed to a highly dynamic physical and chemical environment that can modify their physicochemical properties (Vale et al., 2016). Such physical, chemical, and biological modifications (transformations) are the main processes that will define the behavior of nanoparticles in water (Turan et al., 2019). More specifically, physical processes include homo/hetero aggregation, agglomeration, sedimentation, and deposition (**Fig. 18a**), whereas chemical counterparts encompass photochemical reactions, redox reactions (oxidation, sulfidation), and dissolution (**Fig. 18b**).

These reactions significantly depend on nanoparticle properties (concentration, size, coating material, shape, and oxidation level) and environmental conditions (pH, ionic strength, and dissolved organic matter) (He et al., 2017). **Figure 19** illustrates the adsorption, dissolution, transformation, and stabilization / aggregation behaviors of magnetic

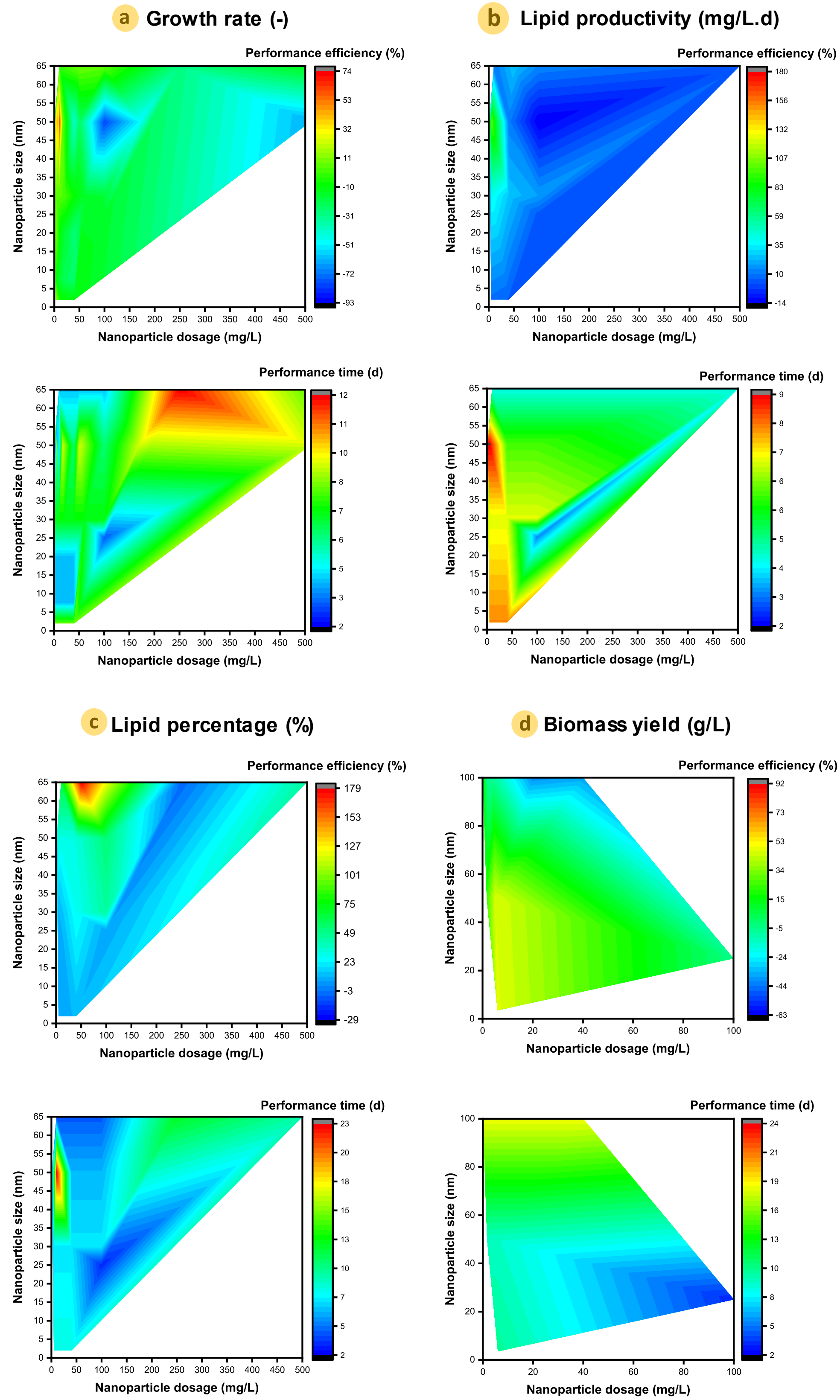


Fig. 16. Contour diagrams indicating the effect of nanoparticle dose and size on the improvement of performance indicators (performance parameters of efficiency and time): **(a)** growth rate, **(b)** lipid productivity, **(c)** lipid percentage, and **(d)** biomass yield during microalgae cultivation. Data obtained from Deng et al. (2017), Estime et al. (2015), Farooq et al. (2016), Guo et al. (2015), He et al. (2017), Jeon et al. (2017), Kadar et al. (2012), Kang et al. (2014), Kim et al. (2016), Mykhaylenko and Zolotareva (2017), Ooms et al. (2015), Pádrová et al. (2015), Rudic et al. (2012), Sarma et al. (2014), Sun et al. (2016 and 2018), Wang and Yang (2013), and Zhang et al. (2016).

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

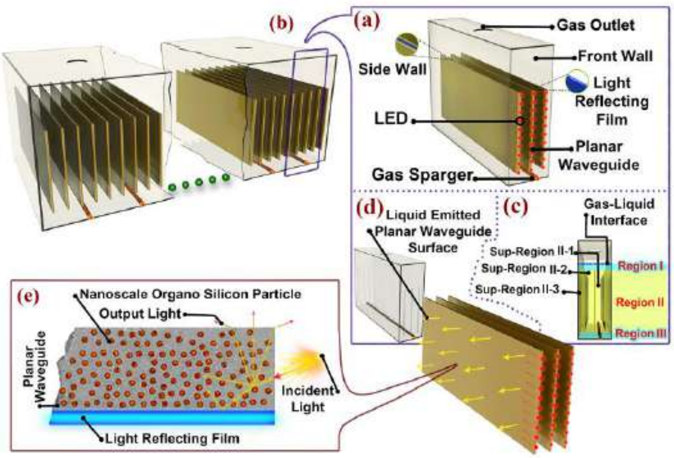


Fig. 17. (a) 3D presentation of one module of the planar waveguide flat-plate photobioreactor, **(b)** 3D presentation of the planar waveguide flat-plate PBR, **(c)** front view of the module of the planar waveguide flat-plate photobioreactor, **(d)** explosive view of the module of the planar waveguide flat-plate photobioreactor, and **(e)** schematic presentation of light-transfer in the planar waveguide doped with light scattering nanoparticles. Adapted and redrawn from Sun et al. (2016).

nanoparticles in the presence of dissolved organic matter. For example, through dissolution (process IV in **Fig. 19**), the common thin oxide coating on zero-valent magnetic nanoparticles (copper(II) oxide on copper zero-valent magnetic nanoparticles) is removed by natural organic matter through the dissolution process. This process allows sufficient oxidation of the exposed zero-valent magnetic nanoparticles with oxygen (copper(I) oxide formation) (Wang et al., 2016b).

Organic matter can generally alter the toxicity of magnetic nanoparticles by modifying ROS generation, steric hindrance, electrostatic repulsion, bioavailability of the dissolved nanoparticles, and suspension stabilization (**Fig. 20**).

Generally, aggregation/agglomeration increases the size of nanoparticles and decreases their concentration in solution, accelerating deposition (Zhang et al., 2018). The rate and size of metal nanoparticle aggregation positively correlate with their concentrations in suspension. Many environmental factors can influence the aggregation process and the stability of metal nanoparticles in aquatic systems. For example, natural organic matter attaches to the particle surface and increases particle stability, whereas ionic strength not only affects the particle surface charge like the pH values do but also alters the electrical double layer.

It should be noted that the existence of natural nanoparticles, colloids and their aggregates, and metallic pollutants further complicate the physicochemical speciation in the exposure medium and determine different biological reactivity. The key chemo- and bio-dynamic processes driving the interactions in the mixtures of engineered nanoparticles (ENPs) and metallic pollutants with aquatic (micro)organisms are shown in **Figure 21** (Li et al., 2020).

Exposure to high doses of nanoparticles may reduce biomass and lipid production by suppressing microalgae growth through a direct or indirect mechanism (**Fig. 16**). The former is done by the adhesion of nanoparticles onto cell membranes, leading to their disruption (**Fig. 22**) (Chen et al., 2019). In comparison, the latter is attributed to the occurrence of nanoparticle agglomeration or aggregation (He et al., 2017). These phenomena could reduce the available light necessary for algal growth (shading effect or entrapment) and limit nutrient uptake by the cells (Deng et al., 2017). ZVI (Lei et al., 2016), titanium dioxide (Manzo et al., 2015), and cerium(IV) oxide (Rodea-Palomares et al., 2012) nanoparticles have been experimentally shown to inhibit microalgae growth by triggering both mentioned mechanisms. It should be noted that besides entrapment, nanoparticle agglomeration and aggregation could eventually trigger oxidative stress *via* over-accumulation of intracellular ROS (**Fig. 22**) (Chen et al., 2019). Briefly, ROS generation leads to membrane

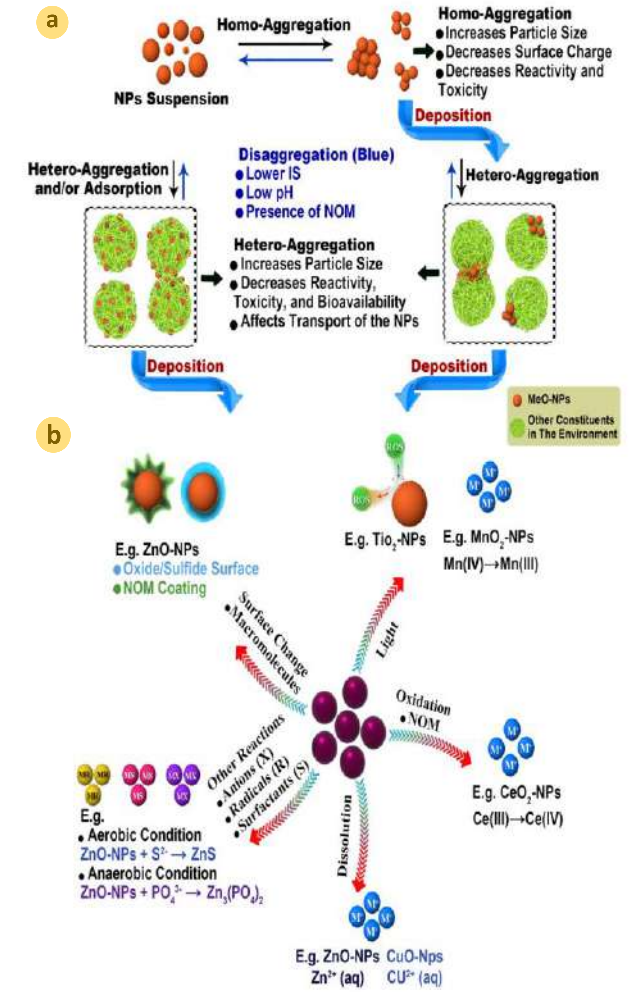


Fig. 18. Common physical **(a)** and chemical **(b)** transformations that nanoparticles undergo in the aquatic environment. Adapted and redrawn from Amde et al. (2017).

lipid peroxidation and over-activation of two antioxidative enzymes, *i.e.*, superoxide dismutase and peroxidase. Once ROS is accumulated beyond the threshold, algal photosynthesis, mitochondrial membrane, and DNA will be compromised. Based on "omics" analysis, genes encoding RuBisCo of carbon fixation (*rbcL*), electron transport chain (*atpA, psbD, petF, psaB, cox3,* and *nad5),* light-harvesting proteins of the photosystem, and the reaction center protein of PSII (*D1*), are suppressed upon exposure to high concentrations of nanoparticles. Moreover, nanoparticles can down-regulate the proteins involved in photosynthesis (cytochrome b6-f complex). These interventions eventually reduce the production of nicotinamide adenine dinucleotide phosphate and adenosine triphosphate, and hence, inhibit the assimilation of carbon dioxide and subsequently decrease the rate of sugar synthesis in the Calvin cycle (Chen et al., 2019).

The algal toxicity of nanoparticles could be affected by their oxidation level. This feature is generally influenced by the age of the nanoparticles and the conditions of their surrounding environment. For example, at similar particle sizes (20–30 nm), the algal toxicity of iron nanoparticles varies proportionally to their oxidation level; ZVI>Fe_3O_4>iron(III) oxide>α-iron(III) oxide>γ-iron(III) oxide (Lei et al., 2016). From the size perspective, the algal toxicity of nanoparticles generally decreases by increasing particle size (Raghupathi et al., 2011) since the reactivity of nanoparticles for agglomeration and co-precipitation with microalgal cells

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

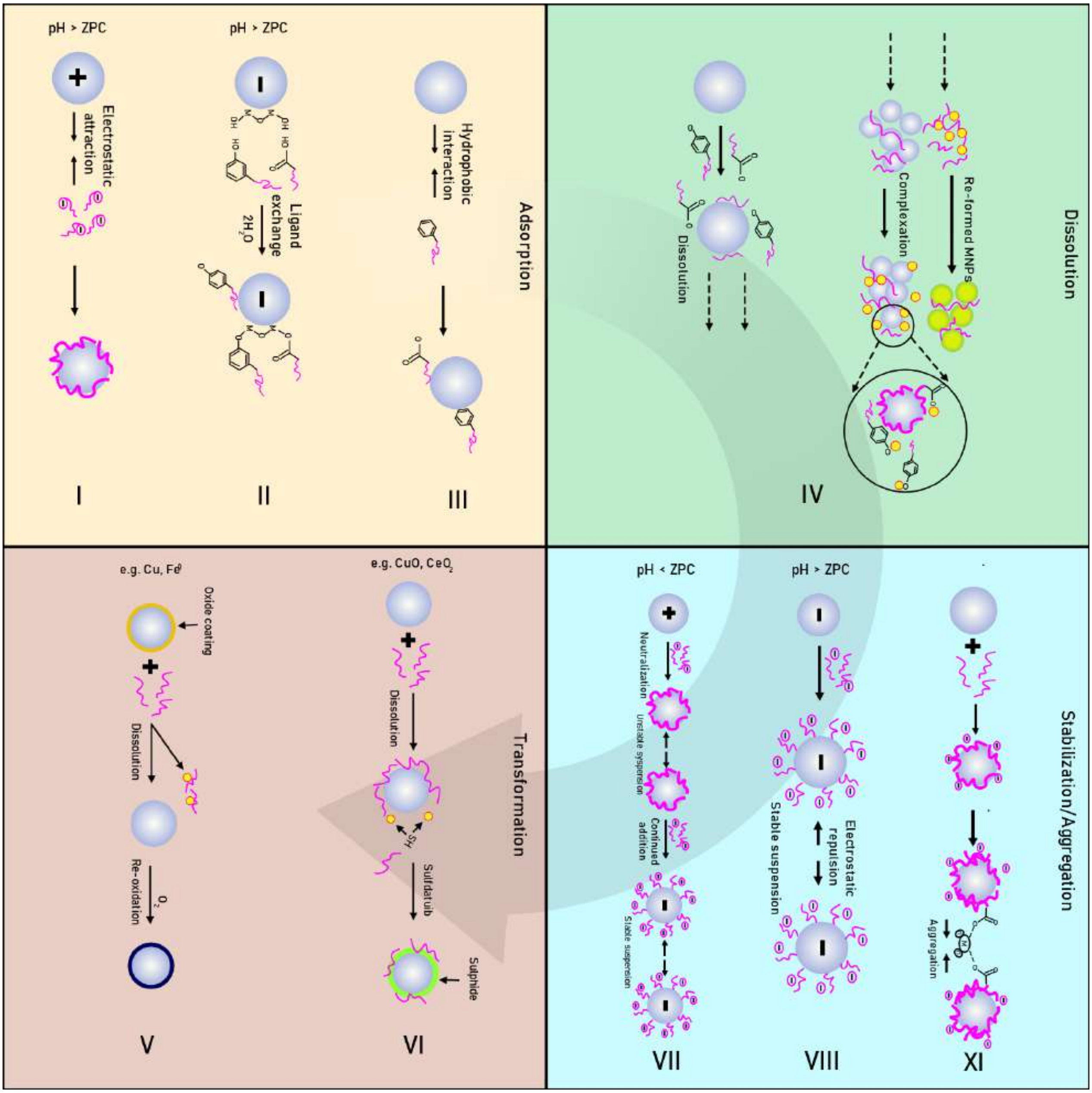


Fig. 19. The effects of natural organic matter on the adsorption (processes **I-III**), dissolution (process **IV**), transformation (processes **V-VI**), and stabilization/aggregation (processes **VII-IX**) behaviors of magnetic nanoparticles in aquatic systems. Adapted from Wang et al. (2016b).

decreases with increasing their size (Lei et al., 2016) (see **Fig. 16** for the relationship between nanoparticle size and performance indices). This issue was experimentally shown by Zhang et al. (2016), who reported that zinc oxide nanoparticles were more toxic on *Skeletonema costatum* than their bulk counterparts. It was observed that the algicidal activity of the zinc oxide nanoparticles was linearly correlated with their intracellular accumulation.

Another mechanism through which some metallic nanoparticles (silver and copper(II) oxide) could cause toxicity is the dissolution of bioavailable metal ions. To investigate that, Angel et al. (2013) experimentally tested the impacts of different coatings on the dissolution rate of silver nanoparticles. It was found that polyvinylpyrrolidone-coated silver nanoparticles had a lower dissolution rate and, subsequently, a lower toxicity effect than their citrate-coated counterparts. Besides the coating materials, the rate of nanoparticle dissolution depends on water organic matter. For example, organic chlorine compounds induced silver nanoparticle dissolution. On the contrary, the dissolution rate of silver nanoparticles decreased with increasing the nanoparticle size, *i.e.*, micron-sized silver nanoparticles had a slower dissolution rate than their nano-sized counterparts (Angel et al., 2013).

Since most nanoparticles used in microalgae cultivation may ultimately enter the natural aquatic environments, studying their effects on microorganisms is of crucial importance. In natural ecosystems, most microorganisms exist in multi-species aggregates (Nozhevnikova et al., 2015). These microbial aggregates comprise a substratum (abiotic and/or biotic) for the attachment of complex consortia of microbial cells (archaea, bacteria, microalgae, protozoa, and fungi) that are embedded in a mucilaginous matrix composed of extracellular polymeric substances (Tang et al., 2018). **Figure 23** outlines the exposure routes of aggregated microorganisms to nanoparticles in an aquatic environment.

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

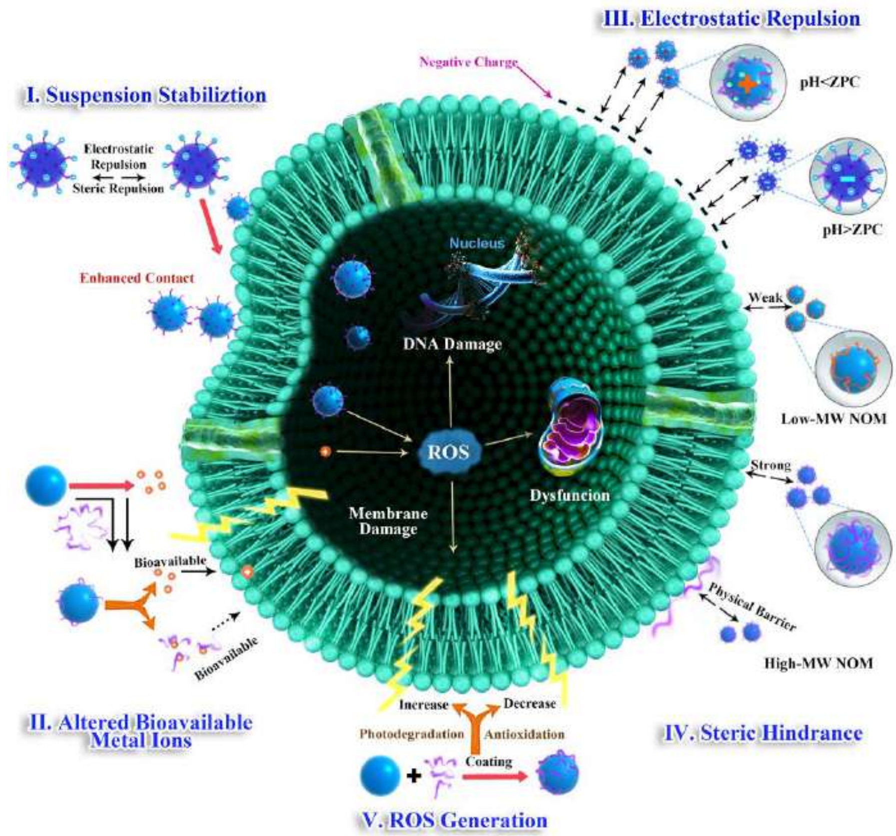


Fig. 20. Different mechanisms for mediating the toxicity of magnetic nanoparticles by natural organic matter in aquatic environments. NOM: Natural organic matter. Adapted from Wang et al. (2016b).

To some extent, the microbial community could adapt itself to nanoparticle exposure. Unlike the planktonic state, higher resistance against nanoparticles is shown by microbial aggregates. This could be obtained through two main mechanisms, including (i) community adaptation and (ii) aggregated structure. **Figure 24** illustrates the key protection mechanisms against nanoparticle exposure in microbial aggregates. A detailed study of these resistance mechanisms is crucial for engineering fewer toxic nanoparticles for beneficial microorganisms (Tang et al., 2018).

2.2.2. Microalgae biomass harvesting

Microalgae harvesting is one of the main challenges associated with their application as biodiesel feedstock (Lee et al., 2015b). Centrifugation, scraping, flotation, filtration, and flocculation-coagulation are the main technologies commonly used for harvesting microalgae (Hu et al., 2013). However, the existing technologies generally have low economic feasibility for microalgae biomass separation (Kumar et al., 2022b; Lapeñas et al., 2022). This issue is attributed to the low concentrations (typically <1.5 g/L) and small size (~10 μm) of microalgae cells, stabilizing their suspension in a culture medium (Fraga-García et al., 2018). The mentioned constraint could be efficiently overcome using nanoparticles or their composites as flocculating agents. Nanoparticle application could replace the need for hazardous chemicals in the microalgae harvesting process (Ge et al., 2015c; Patel et al., 2022). **Figure 25** shows the effect of microalgae dose, nanoparticle dose, and nanoparticle size on the performance parameters in the harvesting process. The higher performance parameters (i.e., efficiency and time) in the harvesting process are obtained at microalgae dose, nanoparticle dose, and nanoparticle size in the range of 500–870 mg/L, 7–1250 mg/L, and 11–85 nm, respectively. In general, the lower dose of microalgae and nanoparticles in this process with smaller nanoparticle sizes results in higher performance efficiencies. Nanoparticles with smaller sizes are more likely to pass through the cell walls and interact with cytomembrane and organelles (Bhuvaneshwari et al., 2018; Rana and Prajapati, 2023). In comparison, larger sizes or aggregates of nanoparticles that fail to get through the cell wall can accumulate on the cell surface (Khan et al., 2022; Yang et al., 2022b). Higher doses of nanoparticles also cause charge neutralization, decreasing the flocculation efficiency (Dharani and Balasubramanian, 2016).

The technique involves the interaction between magnetic nanoparticles and microalgae cells, followed by applying an external magnetic field to separate the nanoparticle-microalgae complex. The efficiency of this technique significantly depends on microalgae species, incubation/cultivation age, nanoparticle concentration, culture medium pH, temperature, and both microalgae cell and magnetic nanoparticle surface characteristics (Wang et al., 2015). At the peak value of the microalgae growth phase, the efficiency of magnetic separation is maximum because of higher collisions between magnetic nanoparticles and cells (Hu et al., 2013). Compared to fresh cultures, older cultures have lower surface functional groups. This improves the availability of a given concentration of magnetic nanoparticles to absorb more cells in old cultures and enhance harvest efficiency (Zhang et al., 2012). However, there is an age threshold after which the efficiency declines. More specifically, following the biomass peak point, microalgae cells undergo autolysis, releasing organic matter, and reducing the availability of magnetic nanoparticles for microalgae cells (Wang et al., 2015). Compared to colonial microalgae, unicellular microalgae have larger specific surface areas because of their

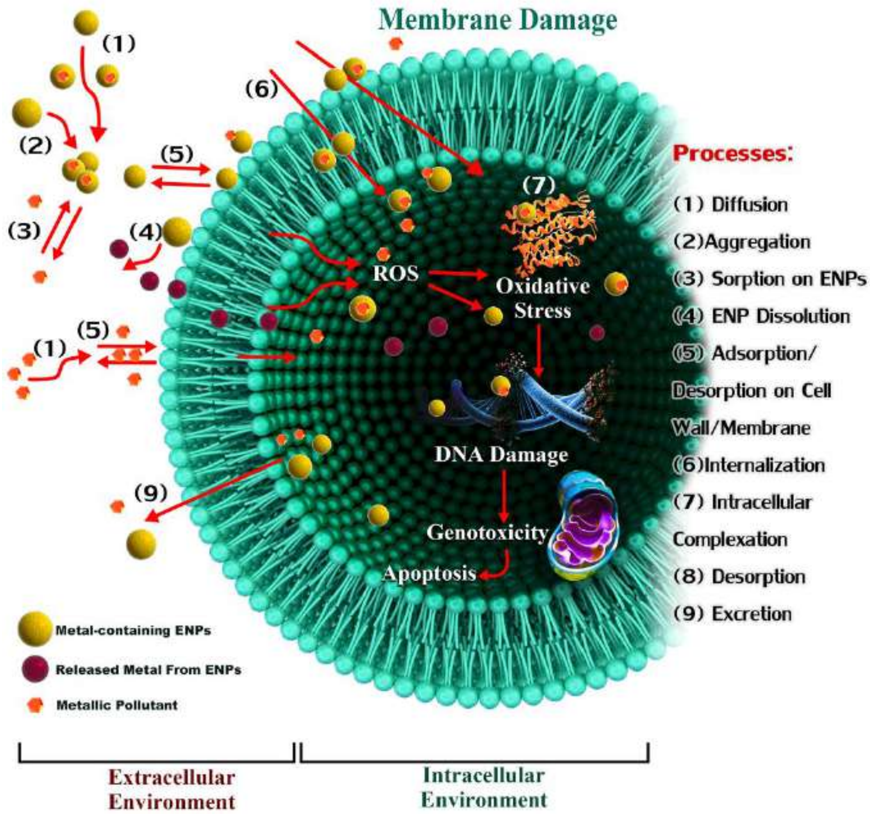


Fig. 21. The key chemo- and bio-dynamic processes driving the interactions in the mixtures of metal-containing ENPs and metallic pollutants with aquatic (micro)organisms. These particles are generally diffused in the medium at different rates and reach the (micro)organism surface **(1)**. ENPs might also aggregate **(2)** or sorb metal pollutants **(3)**. The metal fraction of the ENPs might also release through the dissolution process **(4)**. Once at the organisms' surface, the adsorption of these particles on the cell wall/membrane occurs **(5)**. Following adherence to the cell wall/membrane, the particles can penetrate the cells **(6)** through endocytosis in the case of "particle-ingestive" organisms, alteration in cell membrane permeability in the case of "particle-proof" organisms, or other possible mechanisms. It should be noted that the transportation of dissolved metallic pollutants could be carried out through active (e.g., via essential trace metal transporters) or facilitated (e.g., via channel-mediated diffusion) transportation. Following the transportation into the cells, ENPs, and metallic pollutants interact with intracellular structures and biomolecules, such as DNA, lipids, and proteins, affecting vital cellular processes **(7)**. ENPs or metallic contaminants could also be transformed **(8)** via different methods, such as intracellular complexation, dissolution of engineered nanoparticles, sulfidation, or excreted **(9)**. Adapted from Li et al. (2020).

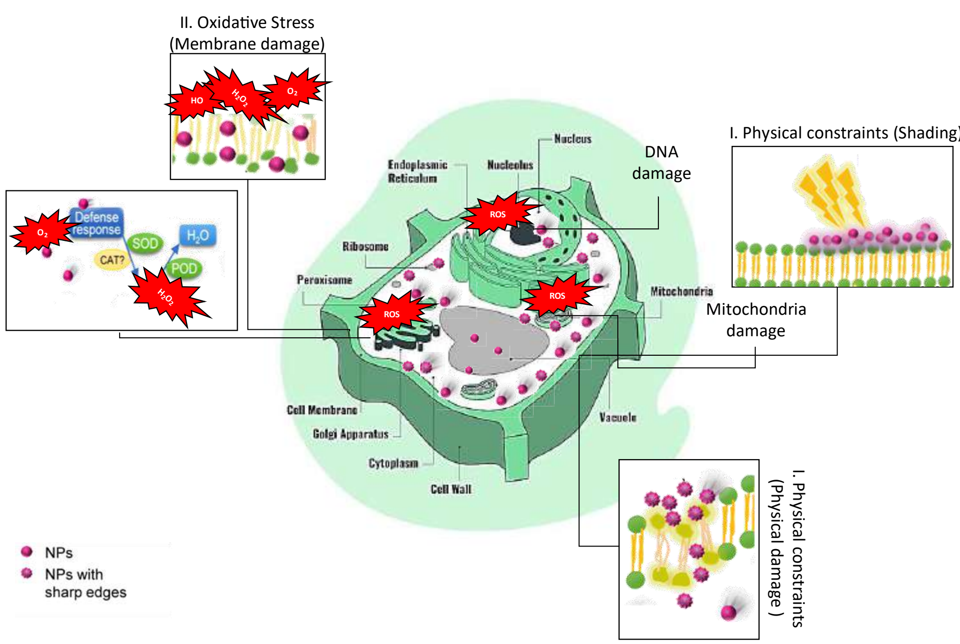


Fig. 22. Schematic representation of the mechanisms of nanoparticles toxicity to microalgae cell membrane and organelles. Adapted and redrawn from Chen et al. (2019).

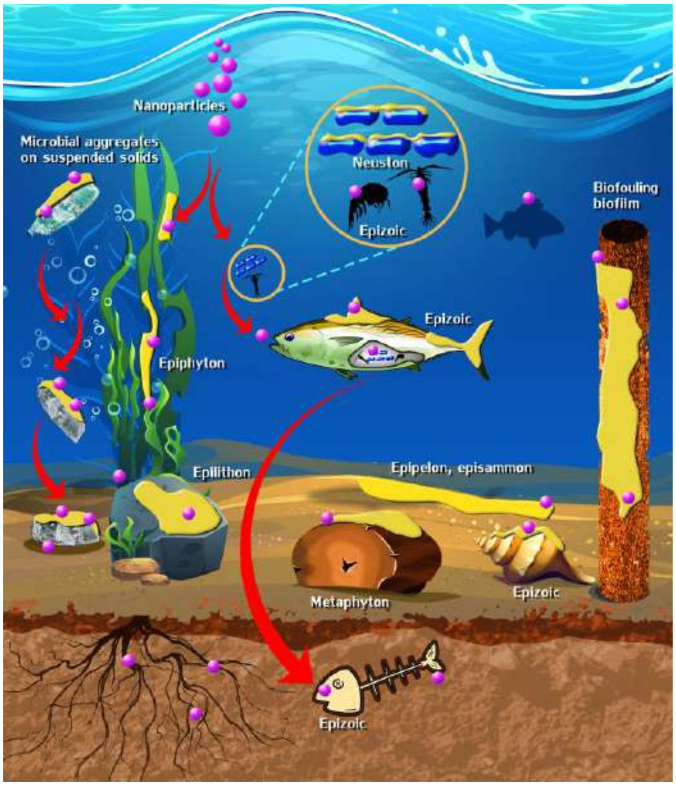


Fig. 23. The fates of nanoparticles within the water column and the sediments in an aquatic ecosystem. Microbial aggregates in aquatic ecosystems can be divided based on the attachment surface into biofouling biofilm, episammon, epipelon, metaphyton, epilithon, epiphyton, epizoic, and neuston. Adapted from Tang et al. (2018).

smaller cell size and, hence, require a lower concentration of magnetic nanoparticles (Xu et al., 2011). The surface charge of most microalgae cells is negative at a wide range of pH values (Hu et al., 2013). For example, *Chlorella* spp. contains abundant hydroxyl and carboxyl groups on their surfaces (Toh et al., 2014b). Therefore, nanoparticles with positively charged surfaces must be used to create an electrostatic attraction and flocculate negatively charged microalgae.

Concerning metal oxides, the pH of the culture medium is another significant parameter influencing their harvest efficiency. This is because the pH of the medium can change the nanoparticles' surface charge by mediating the loss or gain of protons. More specifically, the charge of hydroxyl groups on the surface of metal oxides turns negative and positive at pH above and below the isoelectric point, respectively (Lee et al., 2014a). Hence, metal oxides such as Fe_3O_4 (isoelectric point of 6.8) perform best in an acidic pH range of 4–6 (Hu et al., 2013) while offering negligible magnetic separation efficiencies (~10%) under neutral pH, *i.e.*, 7 due to their negatively charged surfaces (Toh et al., 2014a). The presence of some ions in the culture medium may also affect magnetic separation efficiency. Ions such as magnesium^{2+} and calcium^{2+} improve the flocculation efficiency (Sukenik and Shelef, 1984), whereas some ions, such as phosphate ions (monopotassium phosphate salt), can decrease the efficiency by changing magnetic nanoparticle surface charge from positive to negative (Prochazkova et al., 2013). In addition, the recovery of microalgae biomass is reduced by reducing the temperature of the culture medium. This reduction could be attributed to lower magnetic nanoparticle distribution and mobility at lower temperatures (i.e., higher medium viscosity) (Nassar, 2010).

Nanoparticles used for the magnetic separation of microalgae could be categorized into naked and surface-functionalized magnetic nanoparticles. In fact, naked magnetic nanoparticles could be engineered into functionalized ones to achieve higher harvesting efficiencies. For this purpose, surface coatings and other modifications with materials such as positively charged polymers or cationic surfactants with positively charged functional groups are utilized (Zheng et al., 2016). For instance, a cationic surfactant, *e.g.*, cetylpyridinium bromide, cetylpyridinium chloride, or cetrimonium bromide, can be used for the decoration of Fe_3O_4 nanoparticles

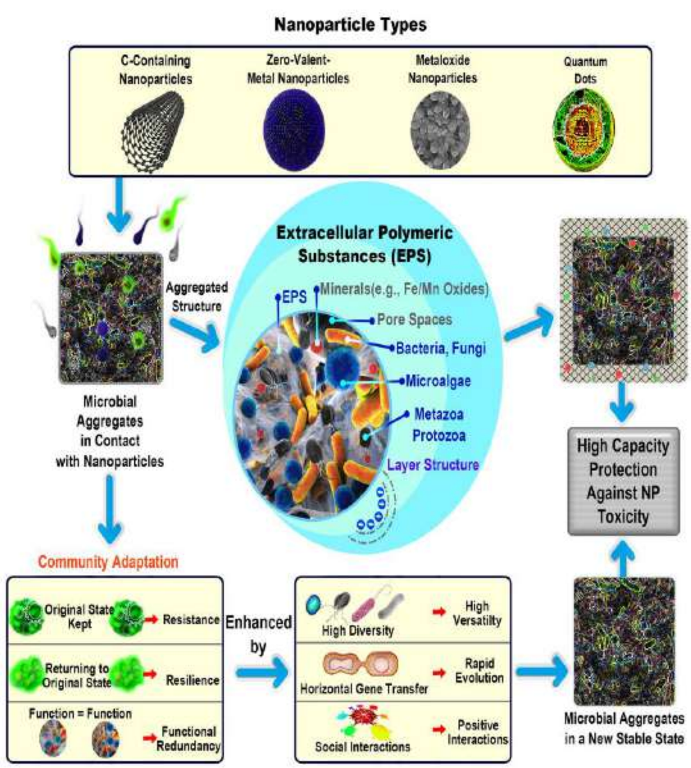


Fig. 24. The main protection mechanisms by microbial aggregates following their exposure to nanoparticles. Adapted from Tang et al. (2018).

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

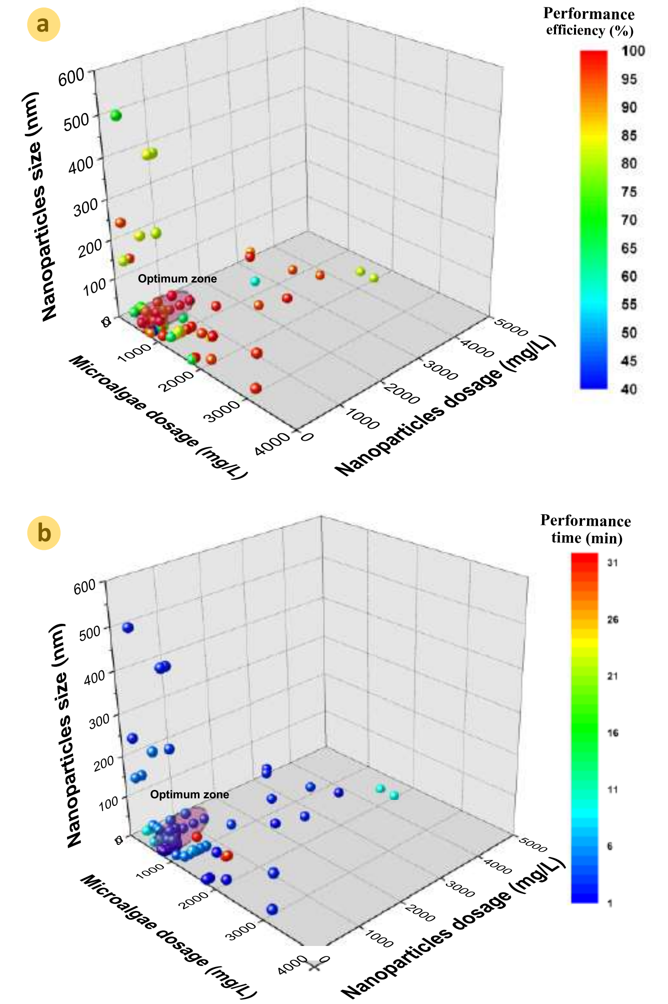


Fig. 25. Effect of microalgae dose, nanoparticle dose, and nanoparticle size on harvesting performance parameters, **(a)** efficiency and **(b)** time. Data obtained from Dineshkumar et al. (2017), Egesa et al. (2018), Farid et al. (2013), Fraga-García et al. (2018), Fu et al. (2021), Ge et al. (2015a and b), Hena et al. (2016), Hu et al. (2013 and 2014a and b), Huang and Kim (2016), Kim et al. (2018), Lee et al. (2013a and 2015), Lee et al. (2013b and 2014b), Lin et al. (2015), Liu et al.(2016b), Liu et al. (2020), Seo et al. (2014 and 2016), Toh et al. (2014 a and b), Tork et al. (2017), Wang et al. (2014a and b), Wang et al. (2016a), Xu et al. (2011), Yang et al. (2018), and Zhu et al. (2019).

(Seo et al., 2016). The resulting positively charged functionalized Fe_3O_4 nanoparticles can easily adhere to negatively charged microalgae through electrostatic attraction and flocculate the algal cells (Seo et al., 2016). Besides simple microalgae separation, the cationic surfactant moiety can also facilitate lipid extraction by solubilizing microalgae cell membranes (Udayan et al., 2022). The nanoparticles are detached from harvested microalgae by inducing repulsion electrostatic force between them by adding sodium dodecyl sulfide (anionic surfactant). Finally, the nanoparticles are magnetically collected and reused (Seo et al., 2016) (**Fig. 26**).

Cationic polyelectrolyte (poly diallyldimethylammonium chloride) (Lim et al., 2012) and cationic polymer (polyethylenimine) (Hu et al., 2014a) were coated on Fe_3O_4 to improve the electrostatic interaction between the nanoparticle and microalgae biomass. The corresponding efficiencies of ~99% and 97% were achieved for the magnetic separation of *Chlorella* sp. and *Corymbia ellipsoidea* in the presence of the Fe_3O_4 nanoparticles, respectively (Lim et al., 2012). Fe_3O_4 nanoparticles coated with cationic polyacrylamide have also been applied for magnetic separation of *C. ellipsoidea* and *Botryococcus braunii* (**Fig. 27**) (Wang et al., 2014a). At pH 7, the adsorption

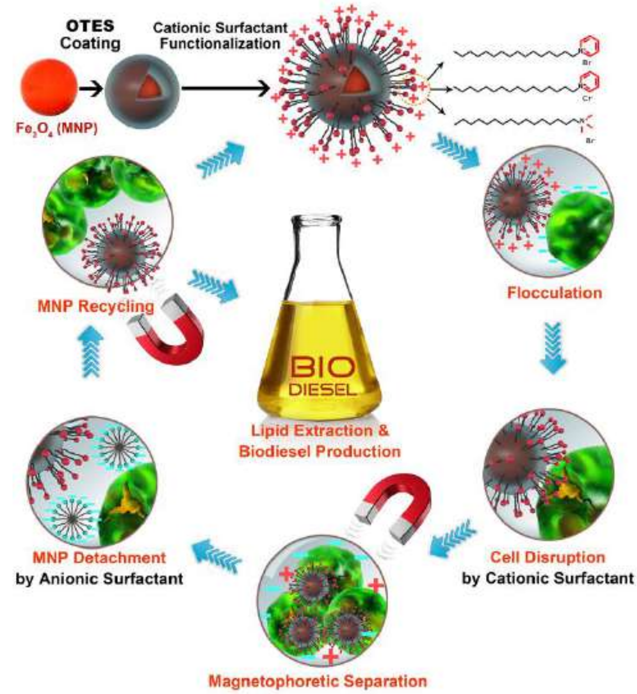


Fig. 26. Schematic representation of the steps involved in a typical harvesting process of microalgae by magnetic nanoparticles. Adapted and redrawn from Seo et al. (2016).

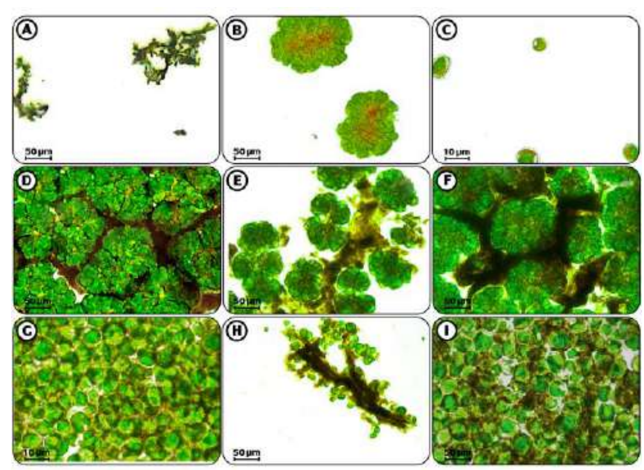


Fig. 27. Light microscope photos of free Fe_3O_4 nanoparticles **(A)**, free microalgal cells **(B, C)**, naked Fe_3O_4 -cell aggregates following magnetic concentration **(D, G)**, CPAM-Fe_3O_4-cell aggregates prior to magnetic concentration **(E, H)**, and CPAM-Fe_3O_4-cell aggregates after magnetic concentration **(F, I)**. (A) ×400; (B, D, E, and F) *B. braunii* (×400); (C, G, and I) *C. ellipsoidea* (×1000); (H) *C. ellipsoidea* (×400). Enhanced from Wang et al. (2014a). With Permission from the American Chemical Society. Copyright© 2014.

capacities, determined by electrostatic attraction, were 21.4 and 114.8 mg dry biomass/mg nanoparticle for *C. ellipsoidea* and *B. braunii*, respectively.

(3-aminopropyl)triethoxysilane-coated barium hexaferrite nanoparticles could deliver a harvesting efficiency of 98.6–99.5% at pH 7 through the magnetic separation of oleaginous *Chlorella* sp. (Seo et al., 2014). Due to their larger surface-to-volume ratios, a stronger electrostatic binding was observed with the smaller-sized functionalized nanoparticles. However, detaching efficiency could be improved by 72.5% to 85% by increasing the

(3-aminopropyl)triethoxysilane-coated nanoparticles size by ~10.8 times (from 108 nm to 1.17 μm) (Seo et al., 2014). Oleaginous *Chlorella* sp. HQ was magnetically separated by sponge-like nanocomposites (graphene-Fe_3O_4/polydiallyldimethylammonium chloride), synthesized using Fe_3O_4, graphene oxide, and cationic polymer diallyldimethylammonium chloride (Liu et al., 2016b). The harvesting performance of the nanocomposites was compared to those of naked Fe_3O_4 and graphene-functionalized Fe_3O_4. A higher harvesting efficiency was achieved by graphene-Fe_3O_4 over Fe_3O_4 (62.7% *vs.* 80.1%) owing to the beneficial contributions (high surface area, lightweight, stable dispersion) of graphene sheets. Incorporating the polymer (graphene-Fe_3O_4 /polydiallyldimethylammonium chloride) further improved the harvesting efficiency of graphene-Fe_3O_4 by 8.6% (Liu et al., 2016b). Moreover, the nanocomposites graphene-Fe_3O_4/polydiallyldimethylammonium chloride showed a wider pH activity range due to the presence of graphene oxide. These advantages could be attributed to the strong interactions (electrostatic attraction and hydrogen bonds) between the graphene sheets and the polymer diallyldimethylammonium chloride through their active sites. The presence of the polymer could improve microalgae flocculation through adsorption bridging and electrostatic interactions of its $nitrogen^+$ groups with the negatively charged microalgae cells.

Magnetic separation is popular because of its economic feasibility and ease of application (Wang et al., 2014b). With the same energy input, greater amounts of biomass and total extracted lipid contents could be obtained when conventional harvesting techniques are replaced by magnetic separation using magnetic nanoparticles, especially using those with cell-disruption capabilities (Seo et al., 2016). The environmental feasibility of the separation process can also be improved by implementing this technique owing to the possibility of recycling both magnetic nanoparticles and the spent culture medium after harvest (Lee et al., 2013a). These advantages reduce energy consumption, water usage, and nanoparticles' negative effects on the environment. Compared to naked magnetic nanoparticles, their functionalized counterparts provide higher separation efficiencies while delivering more rapid processes, lower energy consumption, and wider pH activity ranges (Hu et al., 2014a).

Despite the advantages of magnetic separation, some technical and environmental constraints also exist. One of the main technical issues is the inefficient postharvest separation of magnetic nanoparticles from microalgae biomass under certain circumstances. This issue could significantly affect the environmental and economic feasibilities of the entire process by increasing energy consumption and reducing nanoparticle recycling and the purity of harvested microalgae biomass (Lee et al., 2015a). The technical issue of postharvest separation of magnetic nanoparticles could be, to some extent, overcome by increasing nanoparticle size at the expense of the amount required (Seo et al., 2014). The environmental risks of nanoparticles application (including magnetic ones) were explained earlier.

Magnetic nanoparticles can generate microbial toxicity *via* membrane depolarization and disruption of cell integrity. This is caused by the electrostatic interaction between the negatively charged bacterial membrane and the positively charged cationic polymer or free metal ions (Arias et al., 2018). Alternatively, magnetic nanoparticles can pass through cell membranes *via* passive diffusion, receptor-mediated endocytosis, clathrin-mediated endocytosis, and caveolin-mediated endocytosis (Patil et al., 2018). Upon entering the microbial cell, magnetic nanoparticles are enzymatically broken into $iron^{2+}$ ions (Patil et al., 2018), triggering lipid peroxidation, DNA damage, protein (gene expression), and organelle dysfunctions (actin polymerization, mitochondria) (Arias et al., 2018). Before entering the cells, hydrogen peroxide and other ROS could also be generated on the surface of magnetic nanoparticles through photocatalytic reaction under ultraviolet and visible lights (Xing et al., 2019). The transportation of these oxidative nanoparticles into microbial cells can intensify the mentioned cellular damage.

2.3. Animal fat

Meat production wastes increase with population growth and living standards because of higher demands for processed food. Animal fat is one of the most important fractions of such waste, mainly consumed by the soap and candle production industries, animal feed supplements, and lubricants. However, because of some health concerns, for example, the transmission risk of bovine spongiform encephalopathy by beef tallow, biodiesel production from this low-cost feedstock has grown substantially.

2.3.1. Livestock and poultry

Nanotechnology can improve feed efficiency and nutritional value (faster growth rate) while minimizing disease-related losses in livestock and poultry production (Chen and Yada, 2011). These advantages significantly increase the economic feasibility of animal husbandry, leading to higher fat production and availability for biodiesel production under the biorefinery concept. Nanoparticle-containing food supplements for animals (nanofeed®) enhance animal body defense against pathogens by boosting the immunity system or exerting antimicrobial effects (El Sabry et al., 2018). Additionally, nanoadditives could improve cell activities (as an antioxidant) (Hassan et al., 2017), anticancer mechanisms (Jain et al., 2018), phosphate utilization, and bone growth (Sekhon, 2014) in animals.

Depending on the aim, different nanoparticles, including dendrimer, liposome, polymeric, micellar, ceramic, carbon-based, and metallic nanoparticles (silver, copper, cobalt, iron(II) oxide, titanium dioxide), can be used in animal husbandry (**Table 4**).

Despite the advantages of nanoparticles, some may damage the liver, lungs, and brain (as elaborated earlier). This issue necessitates the green synthesis and use of nanoparticles from plants (*e.g., Aloe vera*, *Camellia sinensis*, *Azadirachta indica*) for future applications. In general, nanomaterials, due to their very small size, are absorbed through the gastrointestinal tract, internalized into cells, and interact with cellular organelles and macromolecules (DNA, ribonucleic acid, protein). The mentioned interactions can cause cell mutation or deficient defense mechanisms by disturbing the biochemical pathways. The causes of genotoxicity induced by nanomaterials are either direct interaction of nanomaterials with genetic material (DNA, ribonucleic acid) or indirect damage by ROS (Dasgupta and Ranjan, 2018).

2.3.2. Aquaculture

With 40–65% oil content, fish and aquaculture wastes are suitable biodiesel feedstocks (Behçet, 2011). In aquaculture, nanotechnology can be used for water purification, quality enhancement, safety (waterborne pathogens removal), and aquatic feed production (Handy, 2012). For example, adding Se nanoparticles (a trace element essential for aquatic health) into the diets of crucian carp significantly increased the growth rate in terms of the final body weight (Zhou et al., 2009). The improvement is attributed to the function of Se as an essential antioxidant activating glutathione peroxidase enzyme. This enzyme plays a key role in cell viability and survival by preventing the Fenton reaction through scavenging hydrogen peroxide and preventing hydroxyl radical formation. The presence of other nanoparticles, such as iron nanoparticles, in sturgeon and young carp diets could also enhance fish growth rate. Notably, nanoparticles could deliver nutrients such as omega fatty acids, lycopene, and vitamins to cells (Jha et al., 2011).

Concerning water quality, the meritorious properties (small size, high reactivity, and large surface area) of iron-manganese binary nano-oxides reportedly allowed an efficient removal of arsenic(III) and arsenic(V) from groundwater before water application in aquaculture (Kong et al., 2013). Calcium-alginate-entrapped nanoscale iron is another functionalized nanoparticle with efficient arsenic removal capability from water resources (Bezbaruah et al., 2014). Lanthanum nanoparticles have been successfully used to absorb phosphates from water and prevent algal growth in fishponds (Ribi -Zelenovi et al., 2009). For pathogen suppression, fungal infections in rainbow trout were effectively prevented using Ag-coated water filters (Johari et al., 2016).

3. Concluding remarks and future directions

The role of nanotechnology and nanomaterials in boosting the productivity of different biodiesel feedstock generations was critically reviewed and discussed. Overall, the following main conclusions can be drawn from the published studies.

I. Because vegetable oils are still the main feedstock for biodiesel, competition can arise with food production. Using chemical fertilizers and pesticides can increase crop yield but pose hazards to humans and the environment. Nanotechnology an help tackle these issues in a

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

Table 4.
Effects of some nanoparticles in livestock and poultry production.*

Nanoparticles	Dose	Application									Domain of effects					Reference
		Antiperiodontitis	Starch digestibility	Growth promoter	Mineral supplementation	Feed additive	Antimicrobial therapy	Antioxidant	Feed digestibility	Antifascioliasis	Microbial	Fungi	Enzyme	Growth, metabolism, and activities	Emissions	
Calcium, zinc, and silver	40 ppm	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	Sanchez et al. (2019)
Citrate-reduced gold and biosynthesized silver	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	Saware et al. (2015)
Citrate-stabilized gold	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	Deka et al. (2012)
Copper	75 mg/kg	-	-	✓	-	-	-	-	-	-	✓	-	-	✓	✓	Refaie et al. (2015)
	7.5 mg/kg	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	Sawosz et al. (2018)
Fullerol $C_{60}(OH)_{24}$	0.1–1 μg/mL	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	Kovač et al. (2018)
Magnesium oxide	0.7–1.4 mg/mL	-	-	-	-	-	✓	-	-	-	✓					Nguyen et al. (2018)
Selenium	0.07–0.60 mg/kg	-	-	-	-	-	-	✓	-	-	-	-	-	-	✓	Mohapatra et al. (2014)
	4 g/kg	-	-	-	-	-	-	-	✓	-	-	-	-	✓	✓	Xun et al. (2012)
Silver	10–40 μg	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	El-Desouky and Ammar (2016)
	90 μg/mL	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	Mousavi and Pourtalebi (2015)
	50 μg/mL	-	-	-	-	-	-	-	-	✓	-	-	-	-	✓	Gherbawy et al. (2013)
Zinc	60 ppm	-	-	-	-	-	-	-	✓	-	-	-	✓		-	Muralisankar et al. (2014)
	20 ppm	-	-	-	-	-	-	✓	-	-	-	-		✓	-	Uniyal et al. (2017)
Zinc oxide	30 ppm	-	-	-	-	-	-	-	✓	-	-	-		✓	-	Ghaffari Chanzanagh et al. (2018)
	30 and 60 mg/kg diet	-	-	-	-	-	-	✓	-	-	-	-	✓	-	-	Hassan et al. (2017)
	1.2 g/kg diet	-	-	-	✓	-	-	-	-	-	-	-	-	✓	✓	Wang et al. (2017)
	2–10 μg/mL	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	Hassan et al. (2013)

* Adopted from Adegbeye et al. (2019).

new way. Fertilizers can be applied in nanoparticle form to deliver micro/macronutrients (e.g., zinc and calcium) or improve the functioning of fertilizers. Nanopesticides can be distributed efficiently on target species because of their small size.

II. The cultivation and harvesting of microalgae can be improved by applying nanotechnology. Harvesting is one of the most important challenges associated with algal biodiesel. Magnetic nanomaterials offer easy scale-up along with fast and gentle processing and could thus be an effective strategy for microalgal harvesting.

III. Nanotechnology could improve the performance and health status of livestock, poultry, and aquaculture systems. These production systems meet human nutritional needs and produce many waste oils/fats that could be used as biodiesel feedstock. Although nanotechnology could enhance crop yield, decrease fertilizer/pesticide loss, and protect the environment by replacing conventional fertilizers/pesticides, its potential negative effects on soil organisms are poorly understood. In addition, the leaching of nanoparticles into water bodies could have detrimental effects on human health and aquatic biota by releasing metal ions. Future studies should examine the leakage of nanoparticles into water bodies and the resulting health issues.

IV. Despite the encouraging findings reported in the published studies about using magnetic nanomaterials in microalgae harvesting, their full retention, recovery, and reuse remain challenging. More specifically, magnetic nanoparticles are sensitive to corrosion in an aquatic environment because of their high reactivity, reducing their lifespan and making their full recovery impractical (Saikia et al., 2019). Accordingly, future research should focus on fully recovering magnetic nanomaterials in algal biodiesel systems, which is crucial from economic and environmental viewpoints.

V. The performance and health status of livestock, poultry, and aquaculture systems could reportedly be improved with the aid of nanotechnology. Nevertheless, the potentially toxic effects of some nanoparticles on living organisms should be evaluated carefully.

Acknowledgments

The authors would like to thank Universiti Malaysia Terengganu under International Partnership Research Grant (UMT/CRIM/2-2/2/23 (23), Vot 55302) for supporting this joint project with Henan Agricultural University under a Research Collaboration Agreement (RCA). This work is also supported by the Ministry of Higher Education, Malaysia, under the Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP) program (Vot. No. 63933 and Vot. No. 56051, UMT/CRIM/2-2/5 Jilid 2 (10) and Vot. No. 56052, UMT/CRIM/2-2/5 Jilid 2 (11)). The manuscript is also supported by the Program for Innovative Research Team (in Science and Technology) in the University of Henan Province (No. 21IRTSTHN020) and Central Plain Scholar Funding Project of Henan Province (No. 212101510005). O.M. would like to thank the support of Tomsk State University Development Programme (Priority-2030) for this research. The authors would also like to extend their sincere appreciation to the University of Tehran and the Biofuel Research Team (BRTeam) for their support throughout this project.

References

[1] Aacharya, R., Chhipa, H., 2020. Nanocarbon fertilizers: implications of carbon nanomaterials in sustainable agriculture production, in: Carbon Nanomaterials for Agri-Food and Environmental Applications. Elsevier, pp. 297-321.

[2] Abdin, Z., Alim, M.A., Saidur, R., Islam, M.R., Rashmi, W., Mekhilef, S., Wadi, A., 2013. Solar energy harvesting with the application of nanotechnology. Renew. Sustain. Energy Rev. 26, 837-852.

[3] Adegbeye, M.J., Elghandour, M.M.M.Y., Barbabosa-Pliego, A., Monroy, J.C., Mellado, M., Salem, A.Z.M., 2019. Nanoparticles in equine nutrition: mechanism of action and application as feed additives. J. Equine Vet. Sci. 78, 29-37.

[4] Adhikari, T., Kundu, S., Biswas, A.K., Tarafdar, J.C., Subba Rao, A., 2015. Characterization of zinc oxide nano particles and their effect on growth of maize (*Zea mays L.*) plant. J. Plant Nutr. 38(10), 1505-1515.

[5] Adhikari, T., Sarkar, D., Mashayekhi, H., Xing, B., 2016. Growth and enzymatic activity of maize (*Zea mays L.*) plant: solution culture test for copper dioxide nano particles. J. Plant Nutr. 39(1), 99-115.

[6] Aratboni, H.A., Rafiei, N., Allaf, M.M., Abedini, S.,Rasheed, R.N., Seif, A., Barati, B., Wang, S., Morones-Ramírez, J.R., 2023. Nanotechnology: an outstanding tool for increasing and better exploitation of microalgae valuable compounds. Algal Res. 71, 103019.

[7] Amde, M., Liu, J.F., Tan, Z.Q., Bekana, D., 2017. Transformation and bioavailability of metal oxide nanoparticles in aquatic and terrestrial environments. a review. Environ. Pollut. 230, 250-267.

[8] Angel, B.M., Batley, G.E., Jarolimek, C.V., Rogers, N.J., 2013. The impact of size on the fate and toxicity of nanoparticulate silver in aquatic systems. Chemosphere. 93(2), 359-365.

[9] Arias, L.S., Pessan, J.P., Vieira, A.P.M., Lima, T.M.T.D., Delbem, A.C.B., Monteiro, D.R., 2018. Iron oxide nanoparticles for biomedical applications: a perspective on synthesis, drugs, antimicrobial activity, and toxicity. Antibiotics. 7(2), 46.

[10] Azam, M., Bhatti, H.N., Khan, A., Zafar, L., Iqbal, M., 2022. Zinc oxide nano-fertilizer application (foliar and soil) effect on the growth, photosynthetic pigments and antioxidant system of maize cultivar. Biocatal. Agric. Biotechnol. 42, 102343.

[11] Babu, S., Singh, R., Yadav, D., Rathore, S.S., Raj, R., Avasthe, R., Yadav, S.K., Das, A., Yadav, V., Yadav, B., Shekhawat, K., 2022. Nanofertilizers for agricultural and environmental sustainability. Chemosphere. 292, 133451.

[12] Behçet, R., 2011. Performance and emission study of waste anchovy fish biodiesel in a diesel engine. Fuel Process. Technol. 92(6), 1187-1194.

[13] Bezbaruah, A.N., Kalita, H., Almeelbi, T., Capecchi, C.L., Jacob, D.L., Ugrinov, A.G., Payne, S.A., 2014. Ca-alginate-entrapped nanoscale iron: arsenic treatability and mechanism studies. J. Nanoparticle Res. 16, 2175.

[14] Bhuvaneshwari, M., Iswarya, V., Chandrasekaran, N., Mukherjee, A., 2018. A review on ecotoxicity of zinc oxide nanoparticles on freshwater algae, in: Nanomaterials: Ecotoxicity, Safety, and Public Perception. Springer, pp. 191-206.

[15] Bluhm, K., Heger, S., Seiler, T.B., Hallare, A.V, Schäffer, A., Hollert, H., 2012. Toxicological and ecotoxicological potencies of biofuels used for the transport sector-a literature review. Energy Environ. Sci. 5(6), 7381-7392.

[16] Bozich, J.S., Lohse, S.E., Torelli, M.D., Murphy, C.J., Hamers, R.J., Klaper, R.D., 2014. Surface chemistry, charge and ligand type impact the toxicity of gold nanoparticles to *Daphnia magna*. Environ. Sci. Nano. 1(3), 260-270.

[17] Cecchin, I., Reddy, K.R., Thomé, A., Tessaro, E.F., Schnaid, F., 2017. Nanobioremediation: integration of nanoparticles and bioremediation for sustainable remediation of chlorinated organic contaminants in soils. Int. Biodeterior. Biodegrad. 119, 419-428.

[18] Chen, F., Xiao, Z., Yue, L., Wang, J., Feng, Y., Zhu, X., Wang, Z., Xing, B., 2019. Algae response to engineered nanoparticles: current understanding, mechanisms and implications. Environ. Sci. Nano. 6(4), 1026-1042.

[19] Chen, H., Yada, R., 2011. Nanotechnologies in agriculture: new tools for sustainable development. Trends Food Sci. Technol. 22(11), 585-594.

[20] Chen, J., Dou, R., Yang, Z., Wang, X., Mao, C., Gao, X., Wang, L., 2016. The effect and fate of water-soluble carbon nanodots in maize (*Zea mays* L.). Nanotoxicology. 10(6), 818-828.

[21] Chen, X., Ji, D., Wang, X., Zang, L., 2017. Review on nano zerovalent iron (nZVI): from modification to environmental applications, in: IOP Conference Series: Earth and Environmental Science. IOP Publishing. 51(1), 12004.

[22] Cheng, F., Liu, Y.F., Lu, G.Y., Zhang, X.K., Xie, L.L., Yuan, C.F., Xu, B.B., 2016. Graphene oxide modulates root growth of *Brassica napus* L. and regulates ABA and IAA concentration. J. Plant Physiol. 193, 57-63.

[23] Chiaramonti, D., Prussi, M., Buffi, M., Rizzo, A.M., Pari, L., 2017. Review and experimental study on pyrolysis and hydrothermal liquefaction of microalgae for biofuel production. Appl. Energy. 185, 963-972.

[24] Cieschi, M.T., Polyakov, A.Y., Lebedev, V.A., Volkov, D.S., Pankratov, D.A., Veligzhanin, A.A., Perminova, I. V, Lucena, J.J., 2019. Eco-friendly iron-humic nanofertilizers synthesis for the prevention of iron chlorosis in soybean (*Glycine max*) grown in calcareous soil. Front. Plant Sci. 10, 413.

[25] Cundy, A.B., Hopkinson, L., Whitby, R.L., 2008. Use of iron-based technologies in contaminated land and groundwater remediation: a review. Sci. Total Environ. 400(1-3), 42-51.

[26] Dasgupta, N., Ranjan, S., 2018. Nano-food toxicity and regulations, in: An Introduction to Food Grade Nanoemulsions. Springer, pp. 151-179.

[27] Dehhaghi, M., Tabatabaei, M., Aghbashlo, M., Panahi, H.K.S., Nizami, A.S., 2019. A state-of-the-art review on the application of nanomaterials for enhancing biogas production. J. Environ. Manage. 251, 109597.

[28] Deka, J., Paul, A., Chattopadhyay, A., 2012. Modulating enzymatic activity in the presence of gold nanoparticles. RSC Adv. 2(11), 4736-4745.

[29] Demirbas, A., 2005. Biodiesel production from vegetable oils via catalytic and non-catalytic supercritical methanol transesterification methods. Prog. Energy Combust. Sci. 31(5-6), 466-487.

[30] Demirbas, A., 2002. Biodiesel from vegetable oils via transesterification in supercritical methanol. Energy Convers. Manage. 43(17), 2349-2356.

[31] Deng, X.Y., Cheng, J., Hu, X.L., Wang, L., Li, D., Gao, K., 2017. Biological effects of TiO_2 and CeO_2 nanoparticles on the growth, photosynthetic activity, and cellular components of a marine diatom *Phaeodactylum tricornutum.* Sci. Total Environ. 575, 87-96.

[32] Dewdar, M., Abbas, M.S., El-Hassanin, A.S., El-Aleem, H.A., 2018. Effect of nano micronutrients and nitrogen foliar applications on sugar beet (*Beta vulgaris* L.) of quantity and quality traits in marginal soils in Egypt. Int. J. Curr. Microbiol. Appl. Sci. 7(08), 4490-4498.

[33] Dharani, M., Balasubramanian, S., 2016. Synthesis, characterization and application of acryloyl chitosan anchored copolymer towards algae flocculation. Carbohydr. Polym. 152, 459-467.

[34] Dineshkumar, R., Paul, A., Gangopadhyay, M., Singh, N.D.P., Sen, R., 2017. Smart and reusable biopolymer nanocomposite for simultaneous microalgal biomass harvesting and disruption: integrated downstream processing for a sustainable biorefinery. ACS Sustainable Chem. Eng. 5(1), 852-861.

[35] Ding, Y., Kuhlbusch, T.A., Van Tongeren, M., Jiménez, A.S., Tuinman, I., Chen, R., Alvarez, I.L., Mikolajczyk, U., Nickel, C., Meyer, J., 2017. Airborne engineered nanomaterials in the workplace-a review of release and worker exposure during nanomaterial production and handling processes. J. Hazard. Mater. 322, 17-28.

[36] Dueso, C., Muñoz, M., Moreno, F., Arroyo, J., Gil-Lalaguna, N., Bautista, A., Gonzalo, A., Sánchez, J.L., 2018. Performance and emissions of a diesel engine using sunflower biodiesel with a renewable antioxidant additive from bio-oil. Fuel. 234, 276-285.

[37] Duran, S.K., Kumar, P., Sandhu, S.S., 2018. A review on microalgae strains, cultivation, harvesting, biodiesel conversion and engine

implementation. Biofuels. 12(1), 91-102.
[38] Egesa, D., Chuck, C.J., Plucinski, P., 2018. Multifunctional role of magnetic nanoparticles in efficient microalgae separation and catalytic hydrothermal liquefaction. ACS Sustainable Chem. Eng. 6(1), 991-999.
[39] El-Desouky, T.A., Ammar, H.A., 2016. Honey mediated silver nanoparticles and their inhibitory effect on aflatoxins and ochratoxin A. J. Appl. Pharm. Sci. 6(6), 083-090.
[40] El Sabry, M.I., McMillin, K.W., Sabliov, C.M., 2018. Nanotechnology considerations for poultry and livestock production systems-a review. Ann. Anim. Sci. 18(2), 319-334.
[41] Elsayed, A.A., Ahmed, E.G., Taha, Z.K., Farag, H.M., Hussein, M.S., AbouAitah, K., 2022. Hydroxyapatite nanoparticles as novel nano-fertilizer for production of rosemary plants. Sci. Hortic. 295, 110851.
[42] Eroglu, E., Eggers, P.K., Winslade, M., Smith, S.M., Raston, C.L., 2013. Enhanced accumulation of microalgal pigments using metal nanoparticle solutions as light filtering devices. Green Chem. 15(11), 3155-3159.
[43] Esper Neto, M., Britt, D.W., Lara, L.M., Cartwright, A., dos Santos, R.F., Inoue, T.T., Batista, M.A., 2020. Initial development of corn seedlings after seed priming with nanoscale synthetic zinc oxide. Agronomy 10(2), 307.
[44] Estime, B., Ren, D., Sureshkumar, R., 2015. Effects of plasmonic film filters on microalgal growth and biomass composition. Algal Res. 11, 85-89.
[45] Farid, M.S., Shariati, A., Badakhshan, A., Anvaripour, B., 2013. Using nano-chitosan for harvesting microalga *Nannochloropsis* sp. Bioresour. Technol. 131, 555-559.
[46] Farooq, W., Lee, H.U., Huh, Y.S., Lee, Y.C., 2016. *Chlorella vulgaris* cultivation with an additive of magnesium-aminoclay. Algal Res. 17, 211-216.
[47] Fraceto, L.F., Grillo, R., de Medeiros, G.A., Scognamiglio, V., Rea, G., Bartolucci, C., 2016. Nanotechnology in agriculture: which innovation potential does it have?. Front. Environ. Sci. 4, 20.
[48] Fraga-García, P., Kubbutat, P., Brammen, M., Schwaminger, S., Berensmeier, S., 2018. Bare iron oxide nanoparticles for magnetic harvesting of microalgae: from interaction behavior to process realization. Nanomaterials. 8(5), 292.
[49] Fu, Y., Hu, F., Li, H., Cui, L., Qian, G., Zhang, D., Xu, Y., 2021. Application and mechanisms of microalgae harvesting by magnetic nanoparticles (MNPs). Sep. Purif. Technol. 265, 118519.
[50] Garimella, R., Eltorai, A.E., 2017. Nanotechnology in orthopedics. J. Orthop. 14(1), 30-33.
[51] Ge, S., Agbakpe, M., Wu, Z., Kuang, L., Zhang, W., Wang, X., 2015a. Influences of surface coating, UV irradiation and magnetic field on the algae removal using magnetite nanoparticles. Environ. Sci. Technol. 49(2), 1190-1196.
[52] Ge, S., Agbakpe, M., Zhang, W., Kuang, L., 2015b. Heteroaggregation between PEI-coated magnetic nanoparticles and algae: effect of particle size on algal harvesting efficiency. ACS Appl. Mater. Interfaces 7(11), 6102-6108.
[53] Ge, S., Agbakpe, M., Zhang, W., Kuang, L., Wu, Z., Wang, X., 2015c. Recovering magnetic Fe_3O_4-ZnO nanocomposites from algal biomass based on hydrophobicity shift under UV irradiation. ACS Appl. Mater. Interfaces. 7(21), 11677-11682.
[54] Ghafariyan, M.H., Malakouti, M.J., Dadpour, M.R., Stroeve, P., Mahmoudi, M., 2013. Effects of magnetite nanoparticles on soybean chlorophyll. Environ. Sci. Technol. 47(18), 10645-10652.
[55] Ghaffari Chanzanagh, E., Seifdavati, J., Mirzaei Gheshlagh, F.A., Abdi Benamar, H., Sharifi, S.R., 2018. Effect of ZnO nanoparticles on in vitro gas production of some animal and plant protein sources. Kafkas Üniversitesi Vet. Fakültesi Derg. 24(1).
[56] Ghazali, W.N.M.W., Mamat, R., Masjuki, H.H., Najafi, G., 2015. Effects of biodiesel from different feedstocks on engine performance and emissions: a review. Renew. Sustainable Energy Rev. 51, 585-602.
[57] Gherbawy, Y.A., Shalaby, I.M., Abd El-sadek, M.S., Elhariry, H.M., Banaja, A.A., 2013. The anti-fasciolasis properties of silver nanoparticles produced by *Trichoderma harzianum* and their improvement of the anti-fasciolasis drug triclabendazole. Int. J. Mol. Sci. 14(11), 21887-21898.
[58] Giannelli, L., Torzillo, G., 2012. Hydrogen production with the microalga *Chlamydomonas reinhardtii* grown in a compact tubular photobioreactor immersed in a scattering light nanoparticle suspension. Int. J. Hydrogen Energy. 37(22), 16951-16961.
[59] Goh, B.H.H., Ong, H.C., Cheah, M.Y., Chen, W.H., Yu, K.L., Mahlia, T.M.I., 2019. Sustainability of direct biodiesel synthesis from microalgae biomass: a critical review. Renew. Sust. Energy Rev. 107, 59-74.
[60] Goodrum, J.W., Geller, D.P., Adams, T.T., 2003. Rheological characterization of animal fats and their mixtures with# 2 fuel oil. Biomass Bioenergy. 24(3), 249-256.
[61] Guan, H., Chi, D., Yu, J., Li, H., 2010. Dynamics of residues from a novel nano-imidacloprid formulation in soyabean fields. Crop Prot. 29(9), 942-946.
[62] Guerriero, G., Cai, G., 2018. Interaction of Nano-sized nutrients with plant biomass: a review, in: Phytotoxicity of Nanoparticles. Springer, pp. 135-149.
[63] Guo, R., Liu, Y., Chen, J., 2015. Toxic Effect of Nano-TiO_2 and Nano-Carbon on Microcystis Aeruginosa, in: International Conference on Advances in Energy, Environment and Chemical Engineering. Atlantis Press, pp. 700-703
[64] Ha, N.M.C., Nguyen, T.H., Wang, S.L., Nguyen, A.D., 2019. Preparation of NPK nanofertilizer based on chitosan nanoparticles and its effect on biophysical characteristics and growth of coffee in green house. Res. Chem. Intermed. 45, 51-63.
[65] Hamedi, J., Mohammadipanah, F., Panahi, H.K.S., 2015. Biotechnological exploitation of actinobacterial members, in: Halophiles: Biodiversity and Sustainable Exploitation. Springer International Publishing, pp. 57-143.
[66] Handy, R.D., 2012. FSBI briefing paper: nanotechnology in fisheries and aquaculture. Fish. Soc. Br. Isles. 1-29.
[67] Hassan, A.A., Howayda, M.E., Mahmoud, H.H., 2013. Effect of zinc oxide nanoparticles on the growth of mycotoxigenic mould. Stud. Chem. Process. Technol. (SCPT). 1(4), 66-74.
[68] Hassan, F.A.M., Mahmoud, R., El-Araby, I.E., 2017. Growth performance, serum biochemical, economic evaluation and IL6 gene expression in growing rabbits fed diets supplemented with zinc nanoparticles. Zagazig Vet. J. 45(3), 238-249.
[69] Hatami, M., 2017. Toxicity assessment of multi-walled carbon nanotubes on *Cucurbita pepo* L. under well-watered and water-stressed conditions. Ecotoxicol. Environ. Saf. 142, 274-283.
[70] Hayles, J., Johnson, L., Worthley, C., Losic, D., 2017. Nanopesticides: a review of current research and perspectives, in: New Pesticides and Soil Sensors. Elsevier, pp. 193-225.
[71] He, M., Yan, Y., Pei, F., Wu, M., Gebreluel, T., Zou, S., Wang, C., 2017. Improvement on lipid production by *Scenedesmus obliquus* triggered by low dose exposure to nanoparticles. Sci. Rep. 7, 15526.
[72] Hena, S., Fatihah, N., Tabassum, S., Lalung, J., Jing, S.Y., 2016. Magnetophoretic harvesting of freshwater microalgae using polypyrrole/Fe_3O_4 nanocomposite and its reusability. J. Appl. Phycol. 28, 1597-1609.
[73] Hennig, T.B., Bandeira, F.O., Puerari, R.C., Fraceto, L.F., Matias, W.G., 2023. A systematic review of the toxic effects of a nanopesticide on non-target organisms: estimation of protective concentrations using a species sensitivity distribution (SSD) approach-The case of atrazine. Sci. Total Environ. 871, 162094.
[74] Hu, Y.R., Guo, C., Wang, F., Wang, S.K., Pan, F., Liu, C.Z., 2014a. Improvement of microalgae harvesting by magnetic nanocomposites coated with polyethylenimine. Chem. Eng. J. 242, 341-347.
[75] Hu, Y.R., Guo, C., Xu, L., Wang, F., Wang, S.K., Hu, Z., Liu, C.Z., 2014b. A magnetic separator for efficient microalgae harvesting. Bioresour. Technol. 158, 388-391.
[76] Hu, Y.R., Wang, F., Wang, S.K., Liu, C.Z., Guo, C., 2013. Efficient harvesting of marine microalgae *Nannochloropsis maritima* using magnetic nanoparticles. Bioresour. Technol. 138, 387-390.
[77] Huang, W.C., Kim, J.D., 2016. Nickel oxide nanoparticle-based method for simultaneous harvesting and disruption of microalgal cells. Bioresour. Technol. 218, 1290-1293.
[78] Iavicoli, I., Leso, V., Beezhold, D.H., Shvedova, A.A., 2017. Nanotechnology in agriculture: opportunities, toxicological implications, and occupational risks. Toxicol. Appl. Pharmacol. 329, 96-111.
[79] Imhoff, J.F., Labes, A., Wiese, J., 2011. Bio-mining the microbial

treasures of the ocean: new natural products. Biotechnol. Adv. 29(5), 468-482.

[80] Jain, A., Ranjan, S., Dasgupta, N., Ramalingam, C., 2018. Nanomaterials in food and agriculture: an overview on their safety concerns and regulatory issues. Crit. Rev. Food Sci. Nutr. 58(2), 297-317.

[81] Jeon, H.S., Park, S.E., Ahn, B., Kim, Y.K., 2017. Enhancement of biodiesel production in *Chlorella vulgaris* cultivation using silica nanoparticles. Biotechnol. Bioprocess Eng. 22, 136-141.

[82] Jha, Z., Behar, N., Sharma, S.N., Chandel, G., Sharma, D.K., Pandey, M.P., 2011. Nanotechnology: prospects of agricultural advancement. Nano Vis. 1(1), 88-100.

[83] Jiang, D., Zeng, G., Huang, D., Chen, M., Zhang, C., Huang, C., Wan, J., 2018. Remediation of contaminated soils by enhanced nanoscale zero valent iron. Environ. Res. 163, 217-227.

[84] Jiang, L.C., Basri, M., Omar, D., Rahman, M.B.A., Salleh, A.B., Rahman, R.N.Z.R.A., Selamat, A., 2012. Green nano-emulsion intervention for water-soluble glyphosate isopropylamine (IPA) formulations in controlling *Eleusine indica* (*E. indica*). Pestic. Biochem. Physiol. 102(1), 19-29.

[85] Jindal, A.B., Bachhav, S.S., Devarajan, P.V, 2017. *In situ* hybrid nano drug delivery system (IHN-DDS) of antiretroviral drug for simultaneous targeting to multiple viral reservoirs: an *in vivo* proof of concept. Int. J. Pharm. 521(1-2), 196-203.

[86] Johari, S.A., Kalbassi, M.R., Soltani, M., Yu, I.J., 2016. Application of nanosilver-coated zeolite as water filter media for fungal disinfection of rainbow trout (*Oncorhynchus mykiss*) eggs. Aquacult.. Int. 24, 23-38.

[87] Jurewicz, A., Ilyas, S., Uppal, J.K., Ivandic, I., Korsching, S., Mathur, S., 2020. Evaluation of magnetite nanoparticle-based toxicity on embryo-larvae stages of zebrafish (*Danio rerio*). ACS Appl. Nano Mater. 3(2), 1621-1629.

[88] Kadar, E., Rooks, P., Lakey, C., White, D.A., 2012. The effect of engineered iron nanoparticles on growth and metabolic status of marine microalgae cultures. Sci. Total Environ. 439, 8-17.

[89] Kah, M., Beulke, S., Tiede, K., Hofmann, T., 2013. Nanopesticides: state of knowledge, environmental fate, and exposure modeling. Crit. Rev. Environ. Sci. Technol. 43(16), 1823-1867.

[90] Kah, M., Hofmann, T., 2014. Nanopesticide research: current trends and future priorities. Environ. Int. 63, 224-235.

[91] Kalwani, M., Chakdar, H., Srivastava, A., Pabbi, S., Shukla, P., 2022. Effects of nanofertilizers on soil and plant-associated microbial communities: emerging trends and perspectives. Chemosphere. 287, 132107.

[92] Kang, N.K., Lee, B., Choi, G.G., Moon, M., Park, M.S., Lim, J., Yang, J.W., 2014. Enhancing lipid productivity of Chlorella vulgaris using oxidative stress by TiO_2 nanoparticles. Korean J. Chem. Eng. 31, 861-867.

[93] Kelsey, J.W., White, J.C., 2013. Effect of C_{60} fullerenes on the accumulation of weathered *p,p′*-DDE by plant and earthworm species under single and multispecies conditions. Environ. Toxicol. Chem. 32(5), 1117-1123.

[94] Khan, S., Naushad, M., Iqbal, J., Bathula, C., Sharma, G., 2022. Production and harvesting of microalgae and an efficient operational approach to biofuel production for a sustainable environment. Fuel. 311, 122543.

[95] Kim, B., Bui, V.K.H., Farooq, W., Jeon, S.G., Oh, Y.K., Lee, Y.C., 2018. Magnesium aminoclay-Fe_3O_4 (MgAC-Fe_3O_4) hybrid composites for harvesting of mixed microalgae. Energies. 11(6), 1359.

[96] Kim, B., Praveenkumar, R., Lee, J., Nam, B., Kim, D.M., Lee, K., Lee, Y.C., Oh, Y.K., 2016. Magnesium aminoclay enhances lipid production of mixotrophic *Chlorella* sp. KR-1 while reducing bacterial populations. Bioresour. Technol. 219, 608-613.

[97] Kings, A.J., Raj, R.E., Miriam, L.R.M., Visvanathan, M.A., 2017. Cultivation, extraction and optimization of biodiesel production from potential microalgae *Euglena sanguinea* using eco-friendly natural catalyst. Energy Convers. Manage. 141, 224-235.

[98] Kole, C., Kole, P., Randunu, K.M., Choudhary, P., Podila, R., Ke, P.C., Rao, A.M., Marcus, R.K., 2013. Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (*Momordica charantia*). Bmc Biotechnol. 13(1), 37.

[99] Kong, S., Wang, Y., Zhan, H., Yuan, S., Liu, M., Zhou, C., 2013. Arsenite and arsenate removal from contaminated groundwater by nanoscale iron-manganese binary oxides: column studies. Environ. Eng. Sci. 30(11), 689-696.

[100] Kovač, T., Borišev, I., Crevar, B., Kenjerić, F.Č., Kovač, M., Strelec, I., Ezekiel, C.N., Sulyok, M., Krska, R., Šarkanj, B., 2018. Fullerol $C_{60}(OH)_{24}$ nanoparticles modulate aflatoxin B_1 biosynthesis in *Aspergillus flavus*. Sci. Rep. 8(1), 12855.

[101] Kumar, A., Singh, K., Verma, P., Singh, O., Panwar, A., Singh, T., Kumar, Y., Raliya, R., 2022a. Effect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. Sci. Rep. 12(1), 6938.

[102] Kumar, N., Banerjee, C., Negi, S., Shukla, P., 2022b. Microalgae harvesting techniques: updates and recent technological interventions. Crit. Rev. Biotechnol. 43(3), 342-368.

[103] Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Hassan, A.A., Kim, K.H., 2019. Nano-based smart pesticide formulations: emerging opportunities for agriculture. J. Control. Release. 294, 131-153.

[104] Lahiani, M.H., Dervishi, E., Chen, J., Nima, Z., Gaume, A., Biris, A.S., Khodakovskaya, M. V, 2013. Impact of carbon nanotube exposure to seeds of valuable crops. ACS Appl. Mater. Interfaces. 5(16), 7965-7973.

[105] Lahiani, M.H., Nima, Z.A., Villagarcia, H., Biris, A.S., Khodakovskaya, M. V., 2017. Assessment of effects of the long-term exposure of agricultural crops to carbon nanotubes. J. Agric. Food Chem. 66(26), 6654-6662.

[106] Lapeñas, L.A., Peña-Bahamonde, J., Nguyen, H., de Luna, M.D.G., Rodrigues, D.F., 2022. Manganese ferrite nanoparticle-algal cell interaction mechanisms for potential application in microalgae harvesting. Clean. Chem. Eng. 4, 100061.

[107] Larue, C., Pinault, M., Czarny, B., Georgin, D., Jaillard, D., Bendiab, N., Mayne-L'Hermite, M., Taran, F., Dive, V., Carrière, M., 2012. Quantitative evaluation of multi-walled carbon nanotube uptake in wheat and rapeseed. J. Hazard. Mater. 227, 155-163.

[108] Lau, Z.L., Low, S.S., Ezeigwe, E.R., Chew, K.W., Chai, W.S., Bhatnagar, A., Yap, Y.J., Show, P.L., 2022. A review on the diverse interactions between microalgae and nanomaterials: growth variation, photosynthetic performance and toxicity. Bioresour. Technol. 351, 127048.

[109] Lee, K., Lee, S.Y., Na, J.G., Jeon, S.G., Praveenkumar, R., Kim, D.M., Chang, W.S., Oh, Y.K., 2013a. Magnetophoretic harvesting of oleaginous *Chlorella* sp. by using biocompatible chitosan/magnetic nanoparticle composites. Bioresour. Technol. 149, 575-578.

[110] Lee, Y.C., Kim, B., Farooq, W., Chung, J., Han, J.I., Shin, H.J., Jeong, S.H., Park, J.Y., Lee, J.S., Oh, Y.K., 2013b. Harvesting of oleaginous *Chlorella* sp. by organoclays. Bioresour. Technol. 132, 440-445.

[111] Lee, K., Lee, S.Y., Praveenkumar, R., Kim, B., Seo, J.Y., Jeon, S.G., Na, J.G., Park, J.Y., Kim, D.M., Oh, Y.K., 2014a. Repeated use of stable magnetic flocculant for efficient harvest of oleaginous *Chlorella* sp. Bioresour. Technol. 167, 284-290.

[112] Lee, Y.C., Lee, H.U., Lee, K., Kim, B., Lee, S.Y., Choi, M.H., Farooq, W., Choi, J.S., Park, J.Y., Lee, J., 2014b. Aminoclay-conjugated TiO_2 synthesis for simultaneous harvesting and wet-disruption of oleaginous *Chlorella* sp. Chem. Eng. J. 245, 143-149.

[113] Lee, K., Na, J.G., Seo, J.Y., Shim, T.S., Kim, B., Praveenkumar, R., Park, J.Y., Oh, Y.K., Jeon, S.G., 2015a. Magnetic-nanoflocculant-assisted water-nonpolar solvent interface sieve for microalgae harvesting. ACS Appl. Mater. Interfaces. 7(33), 18336-18343.

[114] Lee, Y.C., Lee, K., Oh, Y.K., 2015b. Recent nanoparticle engineering advances in microalgal cultivation and harvesting processes of biodiesel production: a review. Bioresour. Technol. 184, 63-72.

[115] Lefevre, E., Bossa, N., Wiesner, M.R., Gunsch, C.K., 2016. A review of the environmental implications of in situ remediation by nanoscale zero valent iron (nZVI): behavior, transport and impacts on microbial communities. Sci. Total Environ. 565, 889-901.

[116] Lei, C., Zhang, L., Yang, K., Zhu, L., Lin, D., 2016. Toxicity of iron-based nanoparticles to green algae: effects of particle size, crystal phase, oxidation state and environmental aging. Environ. Pollut. 218, 505-512.

[117] Li, M., Liu, W., Slaveykova, V.I., 2020. Effects of mixtures of

engineered nanoparticles and metallic pollutants on aquatic organisms. Environments. 7(4), 27.
[118] Li, S., Li, X., Ho, S.H., 2022. How to enhance carbon capture by evolution of microalgal photosynthesis?. Sep. Purif. Technol. 291, 120951.
[119] Liang, T., Yin, Q., Zhang, Y., Wang, B., Guo, W., Wang, J., Xie, J., 2013. Effects of carbon nanoparticles application on the growth, physiological characteristics and nutrient accumulation in tobacco plants. J. Food, Agric. Environ. 11(3/4), 954-958.
[120] Lim, J.K., Chieh, D.C.J., Jalak, S.A., Toh, P.Y., Yasin, N.H.M., Ng, B.W., Ahmad, A.L., 2012. Rapid magnetophoretic separation of microalgae. Small. 8(11), 1683-1692.
[121] Lin, Z., Xu, Y., Zhen, Z., Fu, Y., Liu, Y., Li, W., Luo, C., Ding, A., Zhang, D., 2015. Application and reactivation of magnetic nanoparticles in *Microcystis aeruginosa* harvesting. Bioresour. Technol. 190, 82-88.
[122] Liu, F., Xiong, F., Fan, Y., Li, J., Wang, H.Z., Xing, G.M., Yan, F.M., Tai, F.J., He, R., 2016a. Facile and scalable fabrication engineering of fullerenol nanoparticles by improved alkaline-oxidation approach and its antioxidant potential in maize. J. Nanopart. Res. 18, 338.
[123] Liu, L., Bilal, M., Duan, X., Iqbal, H.M.N., 2019. Mitigation of environmental pollution by genetically engineered bacteria-current challenges and future perspectives. Sci. Total Environ. 667, 444-454.
[124] Liu, P.R., Zhang, H.L., Wang, T., Yang, W.L., Hong, Y., Hou, Y.L., 2016b. Functional graphene-based magnetic nanocomposites as magnetic flocculant for efficient harvesting of oleaginous microalgae. Algal Res. 19, 86-95.
[125] Liu, P., Wang, T., Yang, Z., Hong, Y., Xie, X., Hou, Y., 2020. Effects of Fe_3O_4 nanoparticle fabrication and surface modification on *Chlorella* sp. harvesting efficiency. Sci. Total Environ. 704, 135286.
[126] Liu, Q., Zhang, X., Zhao, Y., Lin, J., Shu, C., Wang, C., Fang, X., 2013. Fullerene-induced increase of glycosyl residue on living plant cell wall. Environ. Sci. Technol. 47(13), 7490-7498.
[127] Liu, R., Lal, R., 2015. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci. Total Environ. 514, 131-139.
[128] Liu, R., Lal, R., 2014. Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (*Glycine max*). Sci. Rep. 4(1), 5686.
[129] Liu, X., Zhang, F., Zhang, S., He, X., Wang, R., Fei, Z., Wang, Y., 2005. Responses of peanut to nano-calcium carbonate. Plant Nutr. Fertitizer Sci. 11(3), 385-389.
[130] Mahapatra, D.M., Satapathy, K.C., Panda, B., 2022. Biofertilizers and nanofertilizers for sustainable agriculture: phycoprospects and challenges. Sci. Total Environ. 803, 149990.
[131] Manzo, S., Buono, S., Rametta, G., Miglietta, M., Schiavo, S., Di Francia, G., 2015. The diverse toxic effect of SiO_2 and TiO_2 nanoparticles toward the marine microalgae *Dunaliella tertiolecta*. Environ. Sci. Pollut. Res. 22, 15941-15951.
[132] Manzoor, M.A., Shah, I.H., Ali Sabir, I., Ahmad, A., Albasher, G., Dar, A.A., Altaf, M.A., Shakoor, A., 2023. Environmental sustainable: biogenic copper oxide nanoparticles as nano-pesticides for investigating bioactivities against phytopathogens. Environ. Res. 231, 115941.
[133] Mathimani, T., Mallick, N., 2018. A comprehensive review on harvesting of microalgae for biodiesel-Key challenges and future directions. Renew. Sust. Energy Rev. 91, 1103-1120.
[134] Mirbakhsh, M., 2023. Role of Nano-fertilizer in Plants Nutrient Use Efficiency (NUE)-a mini review. arXiv preprint arXiv:2305.14357.
[135] Mishra, A., Kumari, M., Pandey, S., Chaudhry, V., Gupta, K.C., Nautiyal, C.S., 2014. Biocatalytic and antimicrobial activities of gold nanoparticles synthesized by *Trichoderma* sp. Bioresour. Technol. 166, 235-242.
[136] Mohammadi, K., 2015. Grain oil and fatty acids composition of soybean affected by nano-iron chelate, chemical fertilizers and farmyard manure. Arch. Agron. Soil Sci. 61(11), 1593-1600.
[137] Mohapatra, P., Swain, R.K., Mishra, S.K., Behera, T., Swain, P., Behura, N.C., Sahoo, G., Sethy, K., Bhol, B.P., Dhama, K., 2014. Effects of dietary nano-selenium supplementation on the performance of layer grower birds. Asian J. Anim. Vet. Adv. 9(10), 641-652.
[138] Mousavi, S.A.A., Pourtalebi, S., 2015. Inhibitory effects of silver nanoparticles on growth and aflatoxin B_1 production by *Aspergillus Parasiticus*. Iran. J. Med. Sci. 40(6), 501.
[139] Mubeen, I., Mfarrej, M.F.B., Razaq, Z., Iqbal, S., Naqvi, S.A.H., Hakim, F., Mosa, W.F.A., Moustafa, M., Fang, Y., Li, B., 2023. Nanopesticides in comparison with agrochemicals: outlook and future prospects for sustainable agriculture. Plant Physiol. Biochem. 107670.
[140] Mukherjee, A., Majumdar, S., Servin, A.D., Pagano, L., Dhankher, O.P., White, J.C., 2016. Carbon nanomaterials in agriculture: a critical review. Front. Plant Sci. 7, 172.
[141] Muralisankar, T., Bhavan, P.S., Radhakrishnan, S., Seenivasan, C., Manickam, N., Srinivasan, V., 2014. Dietary supplementation of zinc nanoparticles and its influence on biology, physiology and immune responses of the freshwater prawn, *Macrobrachium rosenbergii*. Biol. Trace Elem. Res. 160, 56-66.
[142] Mykhaylenko, N.F., Zolotareva, E.K., 2017. The effect of copper and selenium nanocarboxylates on biomass accumulation and photosynthetic energy transduction efficiency of the green algae *Chlorella vulgaris*. Nanoscale Res. Lett. 12, 147.
[143] Nabi, M.N., Rahman, M.M., Akhter, M.S., 2009. Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions. Appl. Therm. Eng. 29(11-12), 2265-2270.
[144] Nan, B., Mutlu, B., Karaca, G.A., Koç, R.Ç., Özçimen, D., 2023. Bioprospecting Antarctic microalgae as anticancer agent against PC-3 and AGS cell lines. Biochem. Eng. J. 195, 108900.
[145] Nassar, N.N., 2010. Rapid removal and recovery of Pb (II) from wastewater by magnetic nanoadsorbents. J. Hazard. Mater. 184(1-3), 538-546.
[146] Nguyen, K.C., Seligy, V.L., Massarsky, A., Moon, T.W., Rippstein, P., Tan, J., Tayabali, A.F., 2013. Comparison of toxicity of uncoated and coated silver nanoparticles, in: Journal of Physics: Conference Series. IOP Publishing. 429(1), 12025.
[147] Nguyen, M.K., Moon, J.Y., Bui, V.K.H., Oh, Y.K., Lee, Y.C., 2019. Recent advanced applications of nanomaterials in microalgae biorefinery. Algal Res. 41, 101522.
[148] Nguyen, N.Y.T., Grelling, N., Wetteland, C.L., Rosario, R., Liu, H., 2018. Antimicrobial activities and mechanisms of magnesium oxide nanoparticles (nMgO) against pathogenic bacteria, yeasts, and biofilms. Sci. Rep. 8(1), 16260.
[149] Nigam, P.S., Singh, A., 2011. Production of liquid biofuels from renewable resources. Prog. Energy Combust. Sci. 37(1), 52-68.
[150] Nozhevnikova, A.N., Botchkova, E.A., Plakunov, V.K., 2015. Multi-species biofilms in ecology, medicine, and biotechnology. Microbiology. 84, 731-750.
[151] OECD/FAO, 2019. OECD-FAO Agricultural Outlook. OECD Agriculture statistics (database).
[152] Oloumi, H., Mousavi, E.A., Nejad, R.M., 2018. Multi-wall carbon nanotubes effects on plant seedlings growth and cadmium/lead uptake in vitro. Russ. J. plant Physiol. 65, 260-268.
[153] Ooms, M.D., Jeyaram, Y., Sinton, D., 2015. Wavelength-selective plasmonics for enhanced cultivation of microalgae. Appl. Phys. Lett. 106(6), 063902.
[154] Pádrová, K., Lukavský, J., Nedbalová, L., Čejková, A., Cajthaml, T., Sigler, K., Vítová, M., Řezanka, T., 2015. Trace concentrations of iron nanoparticles cause overproduction of biomass and lipids during cultivation of cyanobacteria and microalgae. J. Appl. Phycol. 27, 1443-1451.
[155] Pan, X.H., Nie, D., Guo, X.P., Xu, S., Zhang, D., Cao, F., Guan, X., 2023. Effective control of the tomato wilt pathogen using TiO_2 nanoparticles as a green nanopesticide. Environ. Sci. Nano. 10(5), 1441-1452.
[156] Pandey, G., 2018. Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. Environ. Technol. Innov. 11, 299-307.
[157] Patel, A.K., Kumar, P., Chen, C.W., Tambat, V.S., Nguyen, T.B., Hou, C.Y., Chang, J.S., Dong, C.D., Singhania, R.R., 2022. Nano magnetite assisted flocculation for efficient harvesting of lutein and lipid producing microalgae biomass. Bioresour. Technol. 363, 128009.
[158] Patil, R.M., Thorat, N.D., Shete, P.B., Bedge, P.A., Gavde, S., Joshi, M.G., Tofail, S.A.M., Bohara, R.A., 2018. Comprehensive cytotoxicity studies of superparamagnetic iron oxide nanoparticles. Biochem. Biophys. Rep. 13, 63-72.
[159] Paz-Trejo, C., Flores-Márquez, A.R., Gómez-Arroyo, S., 2023. Nanotechnology in agriculture: a review of genotoxic studies of

nanopesticides in animal cells. Environ. Sci. Pollut. Res. 30, 6473-66485.

[160] Pérez-de-Luque, A., 2017. Interaction of nanomaterials with plants: What do we need for real applications in agriculture?. Front. Environ. Sci. 5, 12.

[161] Prasad, T.N.V.K.V., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K.R., Sreeprasad, T.S., Sajanlal, P.R., Pradeep, T., 2012. Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. J. Plant Nutr. 35(6), 905-927.

[162] Prochazkova, G., Safarik, I., Branyik, T., 2013. Harvesting microalgae with microwave synthesized magnetic microparticles. Bioresour. Technol. 130, 472-477.

[163] Qian, K., Guo, H., Chen, G., Ma, C., Xing, B., 2018. Distribution of different surface modified carbon dots in pumpkin seedlings. Sci. Rep. 8(1), 7991.

[164] Raghupathi, K.R., Koodali, R.T., Manna, A.C., 2011. Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. Langmuir. 27(7), 4020-4028.

[165] Rana, M.S., Prajapati, S.K., 2023. Multifarious applications of nanoparticles in microalgae for bioenergy generation: State-of-the-art review. J. Environ. Chem. Eng. 11(1), 109145.

[166] Rani, N., Duhan, A., Pal, A., Kumari, P., Beniwal, R.K., Verma, D., Goyat, A., Singh, R., 2023. Are nano-pesticides really meant for cleaner production? an overview on recent developments, benefits, environmental hazards and future prospectives. J. Clean. Prod. 411, 137232.

[167] Ranjan, S., Dasgupta, N., Singh, S., Gandhi, M., 2019. Toxicity and regulations of food nanomaterials. Environ. Chem. Lett. 17, 929-944.

[168] Rashid, M.I., Shahzad, T., Shahid, M., Ismail, I.M.I., Shah, G.M., Almeelbi, T., 2017. Zinc oxide nanoparticles affect carbon and nitrogen mineralization of *Phoenix dactylifera* leaf litter in a sandy soil. J. Hazard. Mater. 324, 298-305.

[169] Ray, A., Nayak, M., Ghosh, A., 2022. A review on co-culturing of microalgae: a greener strategy towards sustainable biofuels production. Sci. Total Environ. 802, 149765.

[170] Reetu, Clifford, M., Prakash, R., Rai, M.P., 2023. Latest advances and status analysis of nanomaterials for microalgae photosystem, lipids and biodiesel: a state of art. J. Environ. Chem. Eng. 11, 109111.

[171] Refaie, A.M., Ghazal, M.N., Easa, F.M., Barakat, S.A., Morsy, W.A., Younan, G.E., Eisa, W.H., 2015. Nano-copper as a new growth promoter in the diet of growing New Zealand white rabbits. Egypt. J. Rabbit Sci. 25(1), 39-57.

[172] Ren, W., Chang, H., Wang, Y., Teng, Y., Ma, W., Luo, Y., 2018. Effect of sulfonated graphene on uptake, translocation, and metabolism of 2,4,4-trichlorobiphenyl in maize seedlings. Environ. Sci. Pollut. Res. 25, 20084-20096.

[173] Ribi -Zelenovi, L., Spasojevi, M., uki, D., Vuji, J., 2009. Modern agriculture and nanotechnology. Acta Agric. Serbica. 14, 13-21.

[174] Rodea-Palomares, I., Gonzalo, S., Santiago-Morales, J., Leganés, F., García-Calvo, E., Rosal, R., Fernández-Piñas, F., 2012. An insight into the mechanisms of nanoceria toxicity in aquatic photosynthetic organisms. Aquat. Toxicol. 122-123, 133-143.

[175] Rudic, V., Cepoi, L., Gutsul, T., Rudi, L., Chiriac, T., Miscu, V., Sadovnic, D., Nicorici, A., 2012. Red algae *porphyridium cruentum* growth stimulated by CdSe quantum dots covered with thioglycerol. J. Nanoelectron. Optoelectron. 7(7), 681-687.

[176] Saikia, J., Gogoi, A., Baruah, S., 2019. Nanotechnology for Water Remediation, in: Environmental Nanotechnology. Springer, pp. 195-211.

[177] Sanchez, M.C., Toledano-Osorio, M., Bueno, J., Figuero, E., Toledano, M., Medina-Castillo, A.L., Osorio, R., Herrera, D., Sanz, M., 2019. Antibacterial effects of polymeric PolymP-n Active nanoparticles. an *in vitro* biofilm study. Dent. Mater. 35(1), 156-168.

[178] Sangeetha, J., Thangadurai, D., Hospet, R., Purushotham, P., Karekalammanavar, G., Mundaragi, A.C., David, M., Shinge, M.R., Thimmappa, S.C., Prasad, R., 2017. Agricultural nanotechnology: concepts, benefits, and risks, in: Nanotechnology: An Agricultural Paradigm. Springer, pp. 1-17.

[179] Sarkar, R.D., Singh, H.B., Kalita, M.C., 2021. Enhanced lipid accumulation in microalgae through nanoparticle-mediated approach, for biodiesel production: a mini-review. Heliyon. 7(9), e08057.

[180] Sarma, S.J., Das, R.K., Brar, S.K., Le Bihan, Y., Buelna, G., Verma, M., Soccol, C.R., 2014. Application of magnesium sulfate and its nanoparticles for enhanced lipid production by mixotrophic cultivation of algae using biodiesel waste. Energy. 78, 16-22.

[181] Sathya, A.B., Thirunavukkarasu, A., Nithya, R., Nandan, A., Sakthishobana, K., Kola, A.K., Sivashankar, R., Tuan, H.A., Deepanraj, B., 2023. Microalgal biofuel production: potential challenges and prospective research. Fuel. 332, 126199.

[182] Satpati, G.G., Dikshit, P.K., Mal, N., Pal, R., Sherpa, K.C., Rajak, R.C., Rather, S.U., Raghunathan, S., Davoodbasha, M.A., 2023. A state of the art review on the co-cultivation of microalgae-fungi in wastewater for biofuel production. Sci. Total Environ. 870, 161828.

[183] Saware, K., Aurade, R.M., Kamala Jayanthi, P.D., Abbaraju, V., 2015. Modulatory effect of citrate reduced gold and biosynthesized silver nanoparticles on -amylase activity. J. Nanopart. 2015.

[184] Sawosz, E., Łukasiewicz, M., Łozicki, A., Sosnowska, M., Jaworski, S. awomir, Niemiec, J., Scott, A., Jankowski, J., Józefiak, D., Chwalibog, A., 2018. Effect of copper nanoparticles on the mineral content of tissues and droppings, and growth of chickens. Arch. Anim. Nutr. 72(5), 396-406.

[185] Sekhon, B.S., 2014. Nanotechnology in agri-food production: an overview. Nanotechnol. Sci. Appl. 7, 31-53.

[186] Seo, J.Y., Lee, K., Lee, S.Y., Jeon, S.G., Na, J.G., Oh, Y.K., Park, S. Bin, 2014. Effect of barium ferrite particle size on detachment efficiency in magnetophoretic harvesting of oleaginous *Chlorella* sp. Bioresour. Technol. 152, 562-566.

[187] Seo, J.Y., Praveenkumar, R., Kim, B., Seo, J.C., Park, J.Y., Na, J.G., Jeon, S.G., Park, S. Bin, Lee, K., Oh, Y.K., 2016. Downstream integration of microalgae harvesting and cell disruption by means of cationic surfactant-decorated Fe_3O_4 nanoparticles. Green Chem. 18(14), 3981-3989.

[188] Ševců, A., El-Temsah, Y.S., Joner, E.J., Černík, M., 2011. Oxidative stress induced in microorganisms by zero-valent iron nanoparticles. Microbes Environ. 26(4), 271-281.

[189] Shang, Y., Hasan, M.K., Ahammed, G.J., Li, M., Yin, H., Zhou, J., 2019. Applications of nanotechnology in plant growth and crop protection: a review. Molecules. 24(14), 2558.

[190] Sharifi, R., Mohammadi, K., Rokhzadi, A., 2016. Effect of seed priming and foliar application with micronutrients on quality of forage corn (*Zea mays*). Environ. Exp. Biol. 14(4), 151-156.

[191] Sharma, N., Singhvi, R., 2017. Effects of chemical fertilizers and pesticides on human health and environment: a review. Int. J. Agric. Environ. Biotechnol. 10(6), 675-680.

[192] Sheykhbaglou, R., Sedghi, M., Shishevan, M.T., Sharifi, R.S., 2010. Effects of nano-iron oxide particles on agronomic traits of soybean. Not. Sci. Biol. 2(2), 112-113.

[193] Singh, A., Bhati, A., Tripathi, K.M., Sonkar, S.K., 2018. Nanocarbons in agricultural plants: can be a potential nanofertilizer?. Nanotechnol. Environ. Sci. 153-190.

[194] Sohrabi, Y., Omer, K.M., Yazdani, M., Sharifi Kalyani, F., 2023. The effect of nano-fertilizer of paulownia on morpho-physiological traits and dry matter yield of basil under different irrigation levels. J. Plant Nutr. 46(9), 1868-1888.

[195] Srivastava, A., Rao, D.P., 2014. Enhancement of seed germination and plant growth of wheat, maize, peanut and garlic using multiwalled carbon nanotubes. Eur. Chem. Bull. 3(5), 502-504.

[196] Stampoulis, D., Sinha, S.K., White, J.C., 2009. Assay-dependent phytotoxicity of nanoparticles to plants. Environ. Sci. Technol. 43(24), 9473-9479.

[197] Sukenik, A., Shelef, G., 1984. Algal autoflocculation-verification and proposed mechanism. Biotechnol. Bioeng. 26(2), 142-147.

[198] Sun, Y., Huang, Y., Liao, Q., Xia, A., Fu, Q., Zhu, X., Fu, J., 2018. Boosting *Nannochloropsis oculata* growth and lipid accumulation in a lab-scale open raceway pond characterized by improved light distributions employing built-in planar waveguide modules. Bioresour. Technol. 249, 880-889.

[199] Sun, Y., Liang, J., Tang, L., Li, H., Zhu, Y., Jiang, D., Song, B., Chen, M., Zeng, G., 2019. Nano-pesticides: a great challenge for biodiversity?. Nano Today. 28, 100757.

[200] Sun, Y., Liao, Q., Huang, Y., Xia, A., Fu, Q., Zhu, X., Zheng, Y., 2016. Integrating planar waveguides doped with light scattering

nanoparticles into a flat-plate photobioreactor to improve light distribution and microalgae growth. Bioresour. Technol. 220, 215-224.
[201] Taha, R.A., Hassan, M.M., Ibrahim, E.A., Baker, N.H.A., Shaaban, E.A., 2016. Carbon nanotubes impact on date palm in vitro cultures. Plant Cell, Tissue Organ Cult. (PCTOC). 127, 525-534.
[202] Talebi, A.F., Mohtashami, S.K., Tabatabaei, M., Tohidfar, M., Bagheri, A., Zeinalabedini, M., Mirzaei, H.H., Mirzajanzadeh, M., Shafaroudi, S.M., Bakhtiari, S., 2013. Fatty acids profiling: a selective criterion for screening microalgae strains for biodiesel production. Algal Res. 2(3), 258-267.
[203] Tan, H., Wang, C., Li, H., Peng, D., Zeng, C., Xu, H., 2020. Remediation of hexavalent chromium contaminated soil by nano-FeS coated humic acid complex in combination with Cr-resistant microflora. Chemosphere. 242, 125251.
[204] Tang, J., Wu, Y., Esquivel-Elizondo, S., Sørensen, S.J., Rittmann, B.E., 2018. How microbial aggregates protect against nanoparticle toxicity. Trends Biotechnol. 36(11), 1171-1182.
[205] Tiwari, D.K., Dasgupta-Schubert, N., Cendejas, L.M.V., Villegas, J., Montoya, L.C., García, S.E.B., 2014. Interfacing carbon nanotubes (CNT) with plants: enhancement of growth, water and ionic nutrient uptake in maize (*Zea mays*) and implications for nanoagriculture. Appl. Nanosci. 4, 577-591.
[206] Toh, P.Y., Ng, B.W., Ahmad, A.L., Chieh, D.C.J., Lim, J., 2014a. The role of particle-to-cell interactions in dictating nanoparticle aided magnetophoretic separation of microalgal cells. Nanoscale. 6(21), 12838-12848.
[207] Toh, P.Y., Ng, B.W., Chong, C.H., Ahmad, A.L., Yang, J.W., Derek, C.J.C., Lim, J., 2014b. Magnetophoretic separation of microalgae: the role of nanoparticles and polymer binder in harvesting biofuel. RSC Adv. 4(8), 4114-4121.
[208] Tork, M.B., Khalilzadeh, R., Kouchakzadeh, H., 2017. Efficient harvesting of marine *Chlorella vulgaris* microalgae utilizing cationic starch nanoparticles by response surface methodology. Bioresour. Technol. 243, 583-588.
[209] Tripathi, D.K., Singh, S., Singh, S., Pandey, R., Singh, V.P., Sharma, N.C., Prasad, S.M., Dubey, N.K., Chauhan, D.K., 2017. An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. Plant Physiol. Biochem. 110, 2-12.
[210] Turan, N.B., Erkan, H.S., Engin, G.O., Bilgili, M.S., 2019. Nanoparticles in the aquatic environment: usage, properties, transformation and toxicity-a review. Process Saf. Environ. Prot. 130, 238-249.
[211] Udayan, A., Sirohi, R., Sreekumar, N., Sang, B.I., Sim, S.J., 2022. Mass cultivation and harvesting of microalgal biomass: current trends and future perspectives. Bioresour. Technol. 344, 126406.
[212] Uniyal, S., Garg, A.K., Jadhav, S.E., Chaturvedi, V.K., Mohanta, R.K., 2017. Comparative efficacy of zinc supplementation from different sources on nutrient digestibility, hemato-biochemistry and anti-oxidant activity in guinea pigs. Livest. Sci. 204, 59-64.
[213] Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S.A., ur Rehman, H., Ashraf, I., Sanaullah, M., 2020. Nanotechnology in agriculture: current status, challenges and future opportunities. Sci. Total Environ. 721, 137778.
[214] Vale, G., Mehennaoui, K., Cambier, S., Libralato, G., Jomini, S., Domingos, R.F., 2016. Manufactured nanoparticles in the aquatic environment-biochemical responses on freshwater organisms: a critical overview. Aquat. Toxicol. 170, 162-174.
[215] Vasistha, S., Balakrishnan, D., Manivannan, A., Rai, M.P., 2023. Microalgae on distillery wastewater treatment for improved biodiesel production and cellulose nanofiber synthesis: a sustainable biorefinery approach. Chemosphere. 315, 137666.
[216] Verma, S.K., Das, A.K., Gantait, S., Kumar, V., Gurel, E., 2019. Applications of carbon nanomaterials in the plant system: a perspective view on the pros and cons. Sci. Total Environ. 667, 485-499.
[217] Vignesh, P., Jayaseelan, V., Pugazhendiran, P., Prakash, M.S., Sudhakar, K., 2022. Nature-inspired nano-additives for Biofuel application-a review. Chem. Eng. J. Adv. 100360.
[218] Vijayakumar, S., Rajapriya, A., Vidhya, E., Nilavukkarasi, M., Punitha, V.N., 2023. Agriculture revolution impact on a modest dosage of silver nano-fertilizer: a green strategy. Chem. Africa. 1-8.
[219] Wang, C., Zhang, Ligen, Su, W., Ying, Z., He, J., Zhang, Lili, Zhong, X., Wang, T., 2017. Zinc oxide nanoparticles as a substitute for zinc oxide or colistin sulfate: effects on growth, serum enzymes, zinc deposition, intestinal morphology and epithelial barrier in weaned piglets. PLoS One. 12(7), e0181136.
[220] Wang, J., Zhu, X., Tan, L., Zhao, T., Ni, Z., Zhang, N., Wang, Jiangtao, 2022. Single and combined nanotoxicity of ZnO nanoparticles and graphene quantum dots against the microalga *Heterosigma akashiwo*. Environ. Sci. Nano. 9(8), 3094-3109.
[221] Wang, S.K., Stiles, A.R., Guo, C., Liu, C.Z., 2015. Harvesting microalgae by magnetic separation: a review. Algal Res. 9, 178-185.
[222] Wang, S.K., Wang, F., Hu, Y.R., Stiles, A.R., Guo, C., Liu, C.Z., 2014a. Magnetic flocculant for high efficiency harvesting of microalgal cells. ACS Appl. Mater. Interfaces. 6(1), 109-115.
[223] Wang, S.K., Wang, F., Stiles, A.R., Guo, C., Liu, C.Z., 2014b. *Botryococcus braunii* cells: ultrasound-intensified outdoor cultivation integrated with in situ magnetic separation. Bioresour. Technol. 167, 376-382.
[224] Wang, T., Yang, W.L., Hong, Y., Hou, Y.L., 2016a. Magnetic nanoparticles grafted with amino-riched dendrimer as magnetic flocculant for efficient harvesting of oleaginous microalgae. Chem. Eng. J. 297, 304-314.
[225] Wang, Z., Zhang, L., Zhao, J., Xing, B., 2016b. Environmental processes and toxicity of metallic nanoparticles in aquatic systems as affected by natural organic matter. Environ. Sci. Nano. 3(2), 240-255.
[226] Wang, Y., Yang, K., 2013. Toxicity of single-walled carbon nanotubes on green microalga *Chromochloris zofingiensis*. Chinese J. Oceanol. Limnol. 31(2), 306-311.
[227] Xiao, M., Xin, J., Fan, J., Ji, B., 2022. Response mechanisms of microalgal-bacterial granular sludge to zinc oxide nanoparticles. Bioresour. Technol. 361, 127713.
[228] Xing, Y., Li, W., Wang, Q., Li, X., Xu, Q., Guo, X., Bi, X., Liu, X., Shui, Y., Lin, H., 2019. Antimicrobial nanoparticles incorporated in edible coatings and films for the preservation of fruits and vegetables. Molecules. 24(9), 1695.
[229] Xiong, J.L., Li, J., Wang, H.C., Zhang, C.L., Naeem, M.S., 2018. Fullerol improves seed germination, biomass accumulation, photosynthesis and antioxidant system in *Brassica napus* L. under water stress. Plant Physiol. Biochem. 129, 130-140.
[230] Xu, L., Guo, C., Wang, F., Zheng, S., Liu, C.Z., 2011. A simple and rapid harvesting method for microalgae by in situ magnetic separation. Bioresour. Technol. 102(21), 10047-10051.
[231] Xue, W., Huang, D., Zeng, G., Wan, J., Cheng, M., Zhang, C., Hu, C., Li, J., 2018. Performance and toxicity assessment of nanoscale zero valent iron particles in the remediation of contaminated soil: a review. Chemosphere. 210, 1145-1156.
[232] Xun, W., Shi, L., Yue, W., Zhang, C., Ren, Y., Liu, Q., 2012. Effect of high-dose nano-selenium and selenium-yeast on feed digestibility, rumen fermentation, and purine derivatives in sheep. Biol. Trace Elem. Res. 150, 130-136.
[233] Yadav, K.K., Singh, J.K., Gupta, N., Kumar, V.J.J.M.E.S., 2017. A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. J. Mater. Env. Sci. 8(2), 740-757.
[234] Yan, S., Zhao, L., Li, H., Zhang, Q., Tan, J., Huang, M., He, S., Li, L., 2013. Single-walled carbon nanotubes selectively influence maize root tissue development accompanied by the change in the related gene expression. J. Hazard. Mater. 246-247, 110-118.
[235] Yang, L., Su, Q., Si, B., Zhang, Y., Zhang, Y., Yang, H., Zhou, X., 2022a. Enhancing bioenergy production with carbon capture of microalgae by ultraviolet spectrum conversion via graphene oxide quantum dots. Chem. Eng. J. 429, 132230.
[236] Yang, Y., Fan, X., Zhang, J., Qiao, S., Wang, X., Zhang, X., Miao, L., Hou, J., 2022b. A critical review on the interaction of iron-based nanoparticles with blue-green algae and their metabolites: from mechanisms to applications. Algal Res. 64, 102670.
[237] Yang, M., Dong, C., Shi, Y., 2023. Nano fertilizer synergist effects on nitrogen utilization and related gene expression in wheat. BMC Plant Biol. 23(1), 26.
[238] Yang, Y., Hou, J., Wang, P., Wang, C., Miao, L., Ao, Y., Xu, Y., Wang, X., Lv, B., You, G., 2018. Interpretation of the disparity in

harvesting efficiency of different types of *Microcystis aeruginosa* using polyethylenimine (PEI)-coated magnetic nanoparticles. Algal Res. 29, 257-265.

[239] Yang, Z., Fang, Z., Zheng, L., Cheng, W., Tsang, P.E., Fang, J., Zhao, D., 2016. Remediation of lead contaminated soil by biochar-supported nano-hydroxyapatite. Ecotoxicol. Environ. Saf. 132, 224-230.

[240] Yin, Z., Zhu, L., Li, S., Hu, T., Chu, R., Mo, F., Hu, D., Liu, C., Li, B., 2020. A comprehensive review on cultivation and harvesting of microalgae for biodiesel production: environmental pollution control and future directions. Bioresour. Technol. 301, 122804.

[241] Yusefi-Tanha, E., Fallah, S., Rostamnejadi, A., Pokhrel, L.R., 2020. Zinc Oxide Nanoparticles (ZnONPs) as Nanofertilizer: Improvement on Seed Yield and Antioxidant Defense System in Soil Grown Soybean (*Glycine max* cv. Kowsar). BioRxiv. 2020-04.

[242] Zhai, G., Gutowski, S.M., Walters, K.S., Yan, B., Schnoor, J.L., 2015. Charge, size, and cellular selectivity for multiwall carbon nanotubes by maize and soybean. Environ. Sci. Technol. 49(12), 7380-7390.

[243] Zhang, C., Wang, J., Tan, L., Chen, X., 2016. Toxic effects of nano-ZnO on marine microalgae *Skeletonema costatum*: attention to the accumulation of intracellular Zn. Aquat. Toxicol. 178, 158-164.

[244] Zhang, J., Guo, W., Li, Q., Wang, Z., Liu, S., 2018. The effects and the potential mechanism of environmental transformation of metal nanoparticles on their toxicity in organisms. Environ. Sci. Nano. 5(11), 2482-2499.

[245] Zhang, W., 2018. Global pesticide use: profile, trend, cost/benefit and more. Proc. Int. Acad. Ecol. Environ. Sci. 8(1), 1-27.

[246] Zhang, X., Amendola, P., Hewson, J.C., Sommerfeld, M., Hu, Q., 2012. Influence of growth phase on harvesting of *Chlorella zofingiensis* by dissolved air flotation. Bioresour. Technol. 116, 477-484.

[247] Zhang, X.L., Yan, S., Tyagi, R.D., Surampalli, R.Y., 2013. Biodiesel production from heterotrophic microalgae through transesterification and nanotechnology application in the production. Renew. Sust. Energy Rev. 26, 216-223.

[248] Zhao, J., Ni, T., Li, J., Lu, Q., Fang, Z., Huang, Q., Zhang, R., Li, R., Shen, B., Shen, Q., 2016a. Effects of organic-inorganic compound fertilizer with reduced chemical fertilizer application on crop yields, soil biological activity and bacterial community structure in a rice-wheat cropping system. Appl. soil Ecol. 99, 1-12.

[249] Zhao, X., Liu, W., Cai, Z., Han, B., Qian, T., Zhao, D., 2016b. An overview of preparation and applications of stabilized zero-valent iron nanoparticles for soil and groundwater remediation. Water Res. 100, 245-266.

[250] Zhao, Q., Wang, S., Lv, Z., Zupanic, A., Guo, S., Zhao, Q., Jiang, L., Yu, Y., 2022. Using nanomaterials to increase the efficiency of chemical production in microbial cell factories: a comprehensive review. Biotechnol. Adv. 59, 107982.

[251] Zheng, H., Mortensen, L.J., Ravichandran, S., Bentley, K., DeLouise, L.A., 2017. Effect of nanoparticle surface coating on cell toxicity and mitochondria uptake. J. Biomed. Nanotechnol. 13(2), 155-166.

[252] Zheng, M., Lu, J., Zhao, D., 2018. Effects of starch-coating of magnetite nanoparticles on cellular uptake, toxicity and gene expression profiles in adult zebrafish. Sci. Total Environ. 622, 930-941.

[253] Zheng, Z., Wang, X., Zhong, X., Hu, B., Liu, H., Yao, M., 2016. Experimental study on the combustion and emissions fueling biodiesel/n-butanol, biodiesel/ethanol and biodiesel/2,5-dimethylfuran on a diesel engine. Energy. 115, 539-549.

[254] Zhou, X., Feng, C., 2017. The impact of environmental regulation on fossil energy consumption in China: Direct and indirect effects. J. Clean. Prod. 142, 3174-3183.

[255] Zhou, X., Wang, Y., Gu, Q., Li, W., 2009. Effects of different dietary selenium sources (selenium nanoparticle and selenomethionine) on growth performance, muscle composition and glutathione peroxidase enzyme activity of crucian carp (*Carassius auratus gibelio*). Aquaculture. 291(1-2), 78-81.

[256] Zhu, L.D., Hiltunen, E., Li, Z., 2019. Using magnetic materials to harvest microalgal biomass: evaluation of harvesting and detachment efficiency. Environ. Technol. 40(8), 1006-1012.

[257] Zhu, L., Nugroho, Y.K., Shakeel, S.R., Li, Z., Martinkauppi, B., Hiltunen, E., 2017. Using microalgae to produce liquid transportation biodiesel: what is next?. Renew. Sust. Energy Rev. 78, 391-400.

Homa Hosseinzadeh-Bandbafha holds a PhD from the Faculty of Agricultural Engineering and Technology, University of Tehran, Iran. Her research interests primarily include renewable energies, biofuels, life cycle assessment, and sustainability assessment. With over 70 research and review publications in highly referred journals such as *Progress in Energy and Combustion Sciences* (IF: 29.5), *Renewable and Sustainable Energy Reviews*, *Energy Conversion and Management*, *Journal of Hazardous Materials*, and *Energy*, Homa is an established researcher in the field of renewable energies and sustainable assessment (Citations: >3550, h-index: 32, i10 index: 49; August 2023). Homa is also the Editor board of The International Journal of Life Cycle Assessment (Springer; IF: 4.8) and *Resources, Environment and Sustainability* (Elsevier).

Hamed Kazemi Shariat Panahi (1988) received his Master of Science in Microbiology from the University of Tehran and is in his final year of PhD in Neuroscience at Macquarie University. He continued his research activities at University of Tehran on bioremediation and microbial metabolite production, extraction, and purification from 2014 to 2017. In 2018, he joined the Biofuel Research Team (BRTeam) to explore the field of biofuels. His research activities are devoted to producing biofuels and other value-added products under the biorefinery scheme via thermochemical and biochemical processes. He is also interested in associating traffic-related air pollution with human diseases. Hamed has published several articles in highly referred journals such as Renewable Energy, Biotechnology Advances, Seminars in Cancer Biology, Biofuel Research Journal, and Renewable and Sustainable Energy Reviews.

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

Mona Dehhaghi (1988) holds a PhD degree in Microbiology from the University of Tehran. Since joining the Biofuel Research Team (BRTeam) in June 2018, she has managed to publish many articles in several highly referred journals, including Progress in Energy and Combustion Science and Renewable and Sustainable Energy Reviews. Currently, she is pursuing her second PhD course in Neuroscience at Macquarie University. Her main research interests include microbial biotechnology, bioproducts, and finding biomarkers for inflammatory diseases.

Yasin Orooji is a Clarivate Analytics (Web of Science) Highly Cited Researcher and top 1% author in Chemistry and Engineering. He comes from a family of scholars. As the R&D Manager, he worked for Yasin Pajooh Co. from 2012 to 2015; meanwhile, he was awarded the Best Inventor title in 2014 by the Ministry of Science. Later, he was invited to join Professor Wanqin Jin's Research Group in 2015. In 2018, he joined the School of Materials Science and Engineering of Nanjing Forestry University as an associate professor and was promoted to full Professor in 2020. Currently, he is serving as a Distinguished Professor at Zhejiang Normal University and has been listed among the Stanford-Elsevier top 2% scientists since 2021. Since 2017, he has published more than 170 SCI papers (39 ESI top papers, including 2 hot papers) and 10 patents, one of which is the best national patent award. He has about 1120 hours of teaching experience and more than 4200 hours of tutoring student research projects. Since 2012, he has had industrial experiences with DHP Engineering, A.O. Smith, and Alfa Laval. He cumulatively participated in more than 33 million yuan of research and industrial projects, making him a unique researcher to expand top research work to industrial products. He aims to bridge the gap between universities and industries following the concept of Honeywell, Tesla Inc., and Lockheed Martin Corporation.

Hossein Shahbeik holds a PhD in Chemical Engineering (Biotechnology) from the Tarbiat Modares University, Iran. He is currently a Postdoctoral Researcher at Henan Agricultural University (China) and Universiti Malaysia Terengganu (Malaysia). Hossein`s research interests primarily include renewable energies, machine learning, thermochemical conversion processes, and sustainability assessment. He has publications in precious journals such as Renewable and Sustainable Energy Reviews and Chemical Engineering Journal. Dr. Shahbeik is the Guest Editor of "e-Prime" (Elsevier). Hossein has worked in the petrochemical industry for seven years as a senior engineer in the field of QC&QA.

Omid Mahian is a full Professor at Faculty of Mechanical Engineering and Mechanics, Ningbo University. He is also a visiting professor of the Department of Chemical Engineering, Imperial College London. Currently, he is a member of the Editorial Board of Energy (Elsevier), Renewable Energy (Elsevier), and Journal of Nanostructures in Chemistry (Springer), a senior associate editor of the Journal of Thermal Analysis and Calorimetry (Springer), and some other journals. His research direction mainly includes the application of nanotechnology in renewable energy (such as nanofluids application in solar collectors and solar desalination) and analysis of thermal systems. So far, he has published more than 100 SCI papers. He has papers in top journals, including Joule, Progress in Energy and Combustion Science, Physics Reports, and Nano Energy. He has received several international awards from conferences and innovation exhibitions for his contribution to the field of heat transfer and renewable energy.

Hassan Karimi-Maleh works as a professor in the School of Resource and Environment, University of Electronics Science and Technology of China (UESTC). He is a highly cited researcher selected by Clarivate Analytics 2018 (cross-filed), 2019 (Agriculture field) and 2020 (cross-filed), 2021 (Chemistry and Agriculture, two categories in one year), and 2022 (Chemistry and Agriculture, two categories in one year) and Top 1% Scientists in Chemistry and Agriculture simultaneously in ISI Essential Science Indicators from 2014 until now. He has published more than 400 SCI research papers with more than 23000 citations and an h-index of 92 (according to WOS report) and 27800 citations and h-index of 100 (according to Google Scholar). He works on the editorial board of more than 20 international journals, such as Alexandria Engineering Journal (co-editor in editor ELSEVIER IF 6.626). He also works as an adjunct Professor at University of Johannesburg, South Africa, and Lebanese American University, Lebanese. His main research interest includes the development of chemically modified sensors and biosensors using DNA and enzymes as biological recognition elements for food, biological, pharmaceutical, and environmental compounds analysis and investigating electrochemistry behavior of electroactive materials such as polymers, organic and inorganic compounds. Recently, he focused on synthesizing nanomaterials and their application in drug delivery and energy storage fields. He has a big network that works in 3 majors: Environmental, Energy, and Sensor.

Alawi Sulaiman is an associate professor in the Faculty of Plantation and Agrotechnology at Universiti Teknologi MARA. He has a Ph.D. degree in Bioprocess Engineering and has published over 90 articles that have received more than 2,000 citations. He has an h-index of 26 in the academic press. His current research interests include biomass utilization for higher-value bioproducts, biogas and biofertilizer production from organic wastes, wastewater treatment, and organic waste management. His Google Scholar profile can be found at the following link:
https://scholar.google.com.my/citations?user=uIluALAAAAAJ&hl=en

Changtong Mei is a professor in the College of Materials Science and Engineering at Nanjing Forestry University, China. He received his PhD degree from Nanjing Forestry University in 2004. He worked in Forintek Canada Corp., Vancouver, for 12 months as a visiting scientist from 2002 to 2003. His research group mostly focuses on bio-composites and fiber reinforced polymers.

Mohammadali Kiehbadroudinezhad (Member, IEEE) attained his Ph.D. in mechanical engineering specializing in biosystems-renewable energies from the University of Tehran, Iran, in 2021. His academic journey has been marked by dedication and excellence in sustainable energy. From 2019 to 2021, Kiehbadroudinezhad was a graduate researcher within the Department of Electrical and Computer Engineering at Dalhousie University in Halifax, Canada. This experience broadened his horizons and enriched his understanding of cutting-edge developments in the field. Currently, Kiehbadroudinezhad occupies the role of a Postdoctoral Fellow within the esteemed Division of Engineering at Saint Mary's University, located in Halifax, Canada. Mohammadali's contributions extend beyond academia, as evidenced by his prolific authorship of multiple research articles in high-impact Q1 journals, as well

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

as his valuable contributions to book chapters focused on the domain of renewable energy. His patents in the field highlight his inventive prowess. Kiehbadroudinezhad expertise lies in the modeling and optimization of hybrid renewable energy systems, with a particular emphasis on the harmonious integration of wind, solar, and tidal energy sources. Furthermore, his investigations extend to energy storage, smart grid technologies, fuel cells, and environmental science, showcasing his holistic approach to solving complex energy challenges. He is a member of the editorial board of Energy Storage and Saving (ESS), where he plays a pivotal role in shaping the discourse around energy storage innovations. In addition to his multifaceted contributions, Kiehbadroudinezhad also holds a position as an Editor on the Editorial Board of Frontiers in Energy Research.

Dr. Abdul-Sattar Nizami has a Master of Science in Engineering from the Chalmers University of Technology, Sweden. He has a Ph.D. in Sustainable Gaseous Biofuel from the School of Civil and Environmental Engineering, University College Cork, Ireland. At University of Toronto, Canada, he worked as a Postdoctoral Fellow on alternative fuels and life cycle studies in the Department of Chemical Engineering & Applied Chemistry. Later, he served as an Assistant Professor and Head of the Solid Waste Management Unit at Center of Excellence in Environmental Studies of King Abdulaziz University, Jeddah, Saudi Arabia. He is currently working as an Associate Professor at Sustainable Development Study Centre, Government College University Lahore, Pakistan. He has published over 200 papers on renewable energy, alternative fuels, waste-to-energy, catalytic pyrolysis, anaerobic digestion, and resource recovery. He has delivered over 50 invited talks and training sessions to various national and international forums. His work has been cited more than 12 thousand times in the peer-review press, with a total impact factor of over 1300 and an H-index of 61. He is a Senior Editor in Renewable & Sustainable Energy Reviews (Elsevier Impact Factor 15.9), Energy & Environment (Sage Impact Factor 4.2), and Frontiers in Energy Research (IF 3.4). He serves as an Editorial Board Member in Bioresource Technology Reports (Elsevier) and Energy Sources Part B (Taylor & Francis IF 4.621). He is also a guest editor in several special issues and a reviewer for many high-impact Journals of Elsevier, ACS, Springer, Wiley, and Taylor and Francis. He is actively involved in community and consultation services to various international organizations, including the European Commission based IF@ULB, National Research Agency (NRA) of France, National Science Centre Poland, World Bank, and UNEP. For the last 3 years, he has been ranked among the Top 2% of Scientists Worldwide by Stanford University, USA. His achievements have been selected as a Role Model by the U.S. Times Higher Education World University Rankings for King Abdulaziz University as No. 1 in the Arab World in 2019. His recent UNEP report, 'Waste Management Outlook for WEST ASIA 2019, WASTE TOWEALTH', is getting huge attention.

Gilles J. Guillemin (born 1967) is an Australian neuroscientist. He received the French Ordre National du Mérite in 2019 in recognition of his work in medical research. He was awarded a Member of the Order of Australia in 2021. Guillemin started his career as a senior research scientist at St Vincent's Private Hospital (1997-2003), then he became an associate professor at the University of New South Wales (2003-2012). In 2011, he was involved in the founding of The Motor Neuron Disease (MND) Research Centre at Macquarie University. He was co-director of the centre from 2011 to 2016. Prof Guillemin's research focus was the identification of blood biomarkers for MND and focus on mechanisms neuroinflammation and neurotoxicity. Prof Guillemin has been studying the involvement of tryptophan catabolism (via the kynurenine pathway- KP) in human several neurodegenerative diseases for more than 20 years. Prof Guillemin and his teams have conducted research that demonstrates the importance of the KP in multiple sclerosis, Alzheimer's disease, and motor neuron disease, which has diagnostic, prognostic, and therapeutic potential. This research has been extended to other diseases such as depression, suicide, autism, and cancers. His more than 380 publications have gained 25900 citations (h-index, 84)."

Su Shiung Lam holds a Ph.D. in Chemical Engineering from Cambridge University and is currently a Professor and Director of the International Centre of Universiti Malaysia Terengganu. He serves as Editor of Environmental Pollution, Journal of Industrial and Engineering Chemistry, and Carbon Capture Science & Technology, Associate Editor for Reviews of Environmental Contamination and Toxicology, Environmental Advances, Environmental Geochemistry, and Health, Frontiers in Energy Research, and Energy & Environment. He leads a research group working mainly on Chemical & Environmental Engineering, focusing on Waste and Biomass Utilization, Waste and Wastewater Treatment, Green Technology, and Pollution Mitigation. Prof. Lam is active in research on the application of thermochemical processes such as pyrolysis and microwave heating in transforming waste and biomass into green energy and products applicable to industry for carbon capture (e.g., CO_2 absorption), carbon emission reduction (e.g., gasification/ pyrolysis of hydrocarbon feedstock, CO_2 utilization, and conversion), and environmental protection. He has secured 30 research grants, filed patents and commercialized inventions from his research team, and published over 440 articles in journals, such as Lancet, Nature, Science, Progress in Energy and Combustion Science, and Renewable and Sustainable Energy Reviews.

Wanxi Peng is a professor at the College of Forestry, Henan Agricultural University, China. He is the Laboratory Director at Henan Province Engineering Research Center for Forest Biomass Value-added Products. Professor Peng is an academician at the International Academy of Ecology & Life Protection Sciences, UN. He is also a fellow of the Engineered Science Society. He has published more than 300 papers with more than 6,000 citations (h-index: 42, May 2023, Scopus).

Xiangmeng Chen, as a postdoctor, works at Henan Province International Collaboration Lab of Forest Resources Utilization and the School of Science of Henan Agricultural University. Engaged in the high-value utilization of biomass resources, the development and application of green fine chemicals, the preparation of new environmental protection materials, and other research fields.

HYU Distinguished Prof. **Ki-Hyun Kim** was at Florida State University for an MSc.(1984-1986) and at University of South Florida for a Ph.D. (1988-1992). He was a Research Associate at ORNL, USA (1992 to 1994). He moved to Sang Ji University, Korea, in 1995. In 1999, he joined Sejong University. In 2014, he moved to the Department of Civil & Environmental Engineering at Hanyang University. His research areas cover the various aspects of research to incorporate "Air Quality & Environmental Engineering" into "Material Engineering" with emphasis on Metal-Organic Frameworks (MOFs). He was awarded as one of the top 10 National Star Faculties in Korea in 2006 and became an academician (Korean Academy of Science and Technology) in 2018. He has been recognized as a 'Highly Cited Researcher (HCR)' in dual fields of 'Environment & Ecology' and 'Engineering' from Clarivate Analytics. He is serving as associate editor of 'Environmental Research', Sensors', and 'Critical Reviews in Environmental Science & Technology'. He has published more than 970 articles, many of which are in leading scientific journals, including 'Chemical Society Reviews', 'Progress in Material Science', 'Progress in Polymer Science', 'Progress in Energy and Combustion Science', 'Chem', 'Nano Energy', and 'Coordination Chemistry Reviews'.

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4

Mortaza Aghbashlo is an Associate Professor of Biosystems Engineering (University of Tehran, Iran). Mortaza has published over 300 publications, including original research papers and reviews in journals such as Joule, Nature Food, Progress in Energy and Combustion Sciences, Trends in Biotechnology, Biotechnology Advances, Nano Energy, and Renewable and Sustainable Energy Reviews (Citations: 16800, h-index: 72, i10 index: 221; Agust 2023, Google Scholar). He is currently also a Visiting Professor at the Henan Agricultural University (China), where he has been contributing to an international collaboration platform for conducting high-profile research projects. Dr. Aghbashlo was listed on the Web of Science Highly Cited Researcher in the Cross-Filed Category in 2021. He is the Co-Editor of the Book Volumes "Biodiesel: From Production to Combustion" and "Fungi in Fuel Biotechnology" which were published by Springer Nature in 2018 and is on the Editorial Board of Progress in Energy and Combustion Sciences (Elsevier), Biofuel Research Journal (BRJ), and e-Prime (Elsevier). Dr. Aghbashlo is also the Guest Editor of Special Issues in Journal of Hazardous Materials and Environmental Research and has formerly served as Associate Editor of Cleaner Environmental Systems (Elsevier; Impact Factor: 5.0). Dr. Aghbashlo has successfully supervised/co-supervised 20 Ph.D/MSc.

Meisam Tabatabaei is a Professor of Environmental Biotechnology at the Universiti Malaysia Terengganu, Malaysia. Over the last decade, Meisam has worked closely with the United Nations Development Program (UNDP) to promote waste-oriented biofuels in the developing world. Since 2016, he has been the lead collaborator of the Lancet Commission on Health and Climate Change, also known as the Lancet Countdown (UCL, UK), an international collaboration of 99 scientists from 51 universities, research institutes, and UN organizations, including the WHO and World Bank. Dr. Tabatabaei has been leading the "marine food security and undernutrition" indicator of The Lancet Countdown. He has published over 400 publications, including original research papers and reviews in journals such as *The Lancet* (Impact Factor: 168.9), *Joule* (Impact Factor: 39.8), *Nature Food* (Impact Factor: 23.2), *Progress in Energy and Combustion Sciences* (Impact Factor: 29.5), *Trends in Biotechnology* (Impact Factor: 17.3), *Renewable and Sustainable Energy Reviews* (Impact Factor: 15.9), *etc*. (Citations: > 26,000, h-index: 82, i10 index: 286; August 2023, Google Scholar). He is currently also a Visiting Professor at the Henan Agricultural University (China), where he has been contributing to an international collaboration platform for conducting high-profile research projects. He holds the Global Ambassador position at the University of Saskatchewan (USask, Canada), working with prominent USask researchers and scholars in the field of Sustainable Aquaculture within the framework of Circular Bioeconomy and with a focus on Climate Change, Future Food, and Indigenous Knowledge Sharing. Dr. Tabatabaei is listed on the Web of Science Highly Cited Researchers List (Top 0.1% of scientists in the world) in the Engineering Category. He is the Editor of the Book Volumes *"Biogas: Fundamentals, Process, and Operation", "Biodiesel: from Production to Combustion"*, and *"Fungi in Fuel Biotechnology",* which have been published by Springer Nature and is in the Editorial/Advisory Board of Progress in Energy and Combustion Sciences (Elsevier), Scientific Reports (Nature Publishing Group), International Journal of Life Cycle Assessment (Springer), Data in Brief (Elsevier), and Energy Sources, Part A: Recovery, Utilization and Environmental Effects (Taylor & Francis). Meisam is the *Associate Editor* of Critical Reviews in Biotechnology (Taylor & Francis; Impact Factor: 9.0) and Resources, Environment, and Sustainability (Elsevier) and Senior Editor of e-Prime (Elsevier). Dr. Tabatabaei is also the Guest Editor of Special Issues in Biotechnology Advances (Elsevier; Impact Factor: 16.0), Renewable & Sustainable Energy Reviews (Elsevier; Impact Factor: 15.9), and Science of the Total Environment (Elsevier; Impact Factor: 9.8), and has formerly served as founding EiC of Biofuel Research Journal, Associate Editor of the Journal of Cleaner Production (Elsevier; Impact Factor: 11.1), and Associate Editor of Cleaner Environmental Systems (Elsevier; Impact Factor: 5.0). Meisam is also the Co-Editor-in-Chief of Elsevier's Book Series on Biomass and Biofuels. Prof. Tabatabaei has successfully supervised/co-supervised 36 Ph.D. (11; 9 as the main supervisor) and MSc. (25; 20 as the main supervisor) students. Meisam has contributed to successful international grant applications of over 7 million USD as a project leader or lead collaborator. Prof. Meisam Tabatabaei is a member of the Clarivate Malaysia *Hall of Fame* (https://clarivate.com/webinars/malaysia-highly-cited-researchers/).

Please cite this article as: Hosseinzadeh-Bandbafha H., Panahi H.K.S., Dehhaghi M., Orooji Y., Shahbeik H., Mahian O., Karimi-Maleh H., Sulaiman A., Mei C., Kiehbadroudinezhad M., Nizami A.S., Guillemin G.G., Lam S.S., Peng W., Chen X., Kim K.H., Aghbashlo M., Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review. Biofuel Research Journal 39 (2023) 1901-1932. DOI: 10.18331/BRJ2023.10.3.4