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ENVIRONMENTAL FATE AND PHYTOTOXICITY OF COSMETIC-RELEVANT CARBON-BASED NANOMATERIALS

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Abstract

The rapid incorporation of carbon-based nanomaterials (CNMs) such as graphene, carbon nanotubes (CNTs), and carbon nanofibers (CNFs) into cosmetic formulations raises questions about their environmental fate and ecotoxicological risks, including phytotoxic effects on terrestrial plants. This paper synthesizes current evidence on (i) environmental pathways and transformation processes that CNMs may undergo from consumer use to environmental release, (ii) mechanisms of phytotoxicity and plant uptake, translocation, and metabolic disruption, and (iii) knowledge gaps and risk-management strategies for a safe-by-design approach in cosmetic nanotechnology. We integrate findings from ecotoxicology, environmental fate studies, plant biology, and cosmetic nanomaterial literature to present a cohesive framework for assessing and mitigating potential ecological impacts. Our synthesis highlights that while CNMs can exhibit beneficial properties in products, their environmental behavior is governed by material form, surface chemistry, aggregation state, and matrix interactions, which in turn modulate phytotoxicity. We identify priorities for standardized exposure scenarios, harmonized analytical methods, and lifecycle assessment to support regulatory decision-making and responsible innovation in nanocosmetics.

Keywords:Carbon-based nanomaterials, Cosmeticnanotechnology,

Environmentalfate,Phytotoxicity,Nanotoxicology,Sustainable nanocosmetics

1.Introduction

Nanotechnology is integral to modern cosmetics, enabling improved delivery of actives, enhanced UV protection, antioxidants, and novel textures. Among CNMs, graphene, CNTs, and CNFs are prominent due to their exceptional mechanical, electrical, and surface properties, which underpin their use in formulations and functional fillers (Georgakilas et al., 2015; Materialwissenschaft Und WerkstofftechnikMaterials Science ForumMicrochimica Acta. However, increasing production and eventual disposal of CNM-containing products necessitate understanding their environmental fate and potential phytotoxicity—critical facets of ecological risk assessments for nanomaterials used in consumer products Environmental Science NanoEnvironmental Science &TechnologyJournal of Nanoscience and Nanotechnology. This paper surveys environmental fate processes (release, transport, transformation, and fate in soils and water) and phytotoxic mechanisms (germination, growth, nutrient uptake, oxidative stress, and gene/metabolite responses) for cosmetic-relevant CNMs, drawing on studies across environmental science, plant biology, and nanotoxicology. We adopt a precautionary, evidence-based stance, emphasizing how material properties (size, coatings, functionalization) influence environmental behavior and plant responses Journal of BotanyProceedings in RadiochemistryEnvironmental Science & Technology.

2. Environmental fate of carbon-based nanomaterials from cosmetics

2.1 Release pathways and environmental entry

Cosmetic products containing CNMs can release nanoscale materials during use (rinsing, washing), down-the-drain disposal, or improper disposal. Environmental exposure scenarios include wastewater effluents, sludge:wastewater treatment plant outputs, and soil passage from land application of biosolids. Reviews of engineered nanoparticles in consumer products emphasize that nanomaterial release is governed by product type, formulation, and matrix interactions, with CNMs representing a significant fraction of carbon-based nanomaterials in cosmetics Environmental Science NanoJournal of Natural Science Research and ReviewJournal of Botany. The environmental entry of CNMs is thus tied to product lifecycle and consumer behavior, as highlighted in contemporary environmental assessments of cosmetic nanomaterials Environmental Science Nano, Journal of Botany.

2.2 Transformation processes in environmental matrices

CNMs released to the environment may undergo several transformations that alter their bioavailability and toxicity. Oxidation, reduction, sulfidation, aggregation/dispersion, and dissolution (where relevant) can be driven by environmental conditions (pH, ionic strength, organic matter, sunlight). For graphene-based materials and CNFs, photo-oxidation and enzymatic or abiotic aging can modify surface functional groups and dispersibility, impacting fate and interactions with biota Nanotechnology for Environmental Engineering, Molecules, Environmental Science & Technology. Recent work on 2D materials such as MoS2 demonstrates that environmental conditions (dissolution, phase changes) can drive structural alterations and modify phytotoxic outcomes, underscoring the broader principle that environmental context dictates nanoparticle behavior Environmental Science & Technology. While direct data on CNMs in cosmetics-specific matrices are still developing, generalizable findings on CNM environmental transformation provide a basis for anticipating CNM fate in soils and waters receiving cosmetic wastes Environmental Science & Technology, Environmental Science & Technology.

2.3 Transport and fate in soils and aquatic systems

The mobility and sorption of CNMs in environmental media are governed by particle size, agglomeration state, surface chemistry, and natural organic matter. CNMs can adsorb onto soil mineral surfaces or dissolve/re-aggregate depending on porewater chemistry, influencing transport to groundwater or surface waters. Meta-analyses and reviews of CNMs in environmental systems emphasize that agglomeration and interactions with natural organic matter largely govern mobility, with species-specific differences among CNTs, CNFs, graphene, and graphene oxide derivatives Journal of Botany, Proceedings in Radiochemistry, Environmental Science & Technology. In aquatic systems, CNMs may persist as dispersed colloids or become part of colloidal or sediment-associated phases, affecting exposure routes for aquatic and terrestrial plants via root or foliar contact if translocated from soil or water Journal of Nanoscience and Nanotechnology, Journal of Botany, Proceedings in Radiochemistry.

2.4 Bioavailability and uptake considerations

Plant uptake of CNMs is influenced by dissolution (for ionic species), surface charge, functionalization, and aggregate size within rhizosphere and endodermal tissues. Graphene-based materials have been shown to interact with roots and influence water and mineral nutrient dynamics in some plant models, with uptake and translocation contingent on material properties and exposure media Journal of Nanoscience and Nanotechnology, Journal of Botany, Environmental Science & Technology. Notably, plant responses can range from growth stimulation to phytotoxic effects, with outcomes dependent on dose, exposure duration, and plant species, reflecting the complexity of CNM-plant interactions in environmental contexts Journal of Nanoscience and Nanotechnology, Molecules, Environmental Science & Technology.

3.Phytotoxicity of cosmetic-relevant CNMs

3.1 Germination and growth effects

Phytotoxic responses to CNMs are species- and dose-dependent. Several studies using carbon-based nanoparticles report variable effects on germination and early growth across plant species. Some carbon nanomaterials can enhance germination and early vigor under certain conditions, while others cause reduced germination, root elongation inhibition, or oxidative stress at higher exposures. For example, carbon nanomaterials such as CNTs have been reported to influence germination positively in some crops, though results are species-specific and context-dependent; graphene oxide and functionalized derivatives can induce root damage or oxidative stress at elevated concentrations in sensitive species Journal of Nanoscience and Nanotechnology Environmental Science &Technology Journal of Nanoscience and Nanotechnology. The complexity of these responses highlights the need for standardized phytotoxicity testing that accounts for matrix effects and realistic environmental exposures Journal of Nanoscience and Nanotechnology, Journal of Botany, Environmental Science & Technology.

3.2 Uptake, translocation, and accumulation in plants

Uptake and translocation of CNMs in plants involve root uptake, vascular transport, and possible accumulation in tissues. Imaging and spectroscopic methods (e.g., TEM, EDS, synchrotron-based techniques) have revealed internalization and distribution patterns for various CNMs in plant systems, with transformation products detected within root or shoot tissues under certain conditions Environmental Science & Technology, Nanotechnology for Environmental Engineering. The extent of translocation and accumulation depends on particle size, surface chemistry, and the plant species, which in turn influence phytotoxic outcomes and metabolomic responses Journal of Nanoscience and Nanotechnology, Environmental Science & Technology.

3.3 Mechanisms of phytotoxicity

Phytotoxicity from CNMs involves multiple pathways, including: Oxidative stress: CNMs can induce reactive oxygen species (ROS) production, lipid peroxidation, and perturbations in antioxidant systems; GO and GO derivatives have been associated with oxidative stress in fruits and tissues under specific exposures Environmental Science & Technology. Disruption of photosynthesis and metabolism: Nanomaterial exposure can perturb carbohydrate and amino acid metabolism, impacting photosynthetic efficiency and energy balance in plants Environmental Science & Technology. Ion homeostasis and signaling: CNMs can alter micronutrient translocation and ion homeostasis, with downstream effects on stomatal conductance, transpiration, and growth Environmental Science & Technology. Physical and structural effects: Accumulation on root surfaces or within tissues can cause mechanical disruption, impaired water uptake, and tissue damage observable via TEM or light microscopy Journal of Nanoscience and Nanotechnology, Environmental Science & Technology.

3.4 Environmental context and phytotoxicity nuance

Disparities in phytotoxic responses across studies reflect differences in nanoparticle type, coating, aggregation state, exposure media (soil, hydroponic, or foliar), plant species, and endpoint metrics. For example, GO can be more toxic to some crops in hydroponic systems than GO derivatives that are less disruptive in soil matrices, highlighting the importance of exposure context for risk assessment Environmental Science & Technology. The literature also indicates that some carbon-based materials can exhibit hormetic effects at low doses, complicating risk communication and regulatory decisions Journal of Nanoscience and Nanotechnology, Environmental Science & Technology.

Methods and measurement considerations for environmental fate and phytotoxicity studies

4.1Characterization of CNMs in environmental and biological matrices

Accurate characterization of CNMs in complex matrices is essential for interpreting fate and toxicity outcomes. Key parameters include particle size distribution, surface charge (zeta potential), surface functional groups, degree of aggregation, and dissolution behavior. Techniques such as TEM/SEM, Raman spectroscopy, XPS, BET surface area, dynamic light scattering (DLS), and zeta potential measurements are routinely used, but real environmental matrices require careful sample preparation to avoid artifacts. The literature emphasizes adequate physicochemical characterization as a prerequisite for interpreting ecological and phytotoxic responses Chemical Reviews, Journal of Nanoscience and Nanotechnology, Journal of Botany, Proceedings in Radiochemistry.

4.2 Exposure design and ecological relevance

Standardized exposure scenarios that reflect realistic consumer-use pathways (e.g., wastewater effluent-associated exposure, soil amended with biosolids, or plant foliage contact via aerosols) are necessary for extrapolating lab findings to environmental risk. Reviews highlight that environmental fate and ecotoxicology data for CNMs are limited by heterogeneous experimental designs; harmonization of exposure conditions and endpoints is needed for cross-study comparisons Environmental Science Nano, Journal of Botany, Environmental Science & Technology. Inclusion of chronic exposure and sub-lethal endpoints (growth, photosynthesis, nutrient status, oxidative stress markers) is recommended to capture ecological relevance Journal of Botany, Environmental Science & Technology.

4.3 Endpoint selection for phytotoxicity

A combination of germination, seedling growth, root/shoot biomass, chlorophyll content, photosynthetic efficiency, oxidative stress markers (ROS, lipid peroxidation, antioxidant enzyme activity), and morphological/anatomical observations provides a comprehensive assessment of CNM phytotoxicity. Molecular endpoints (transcriptomics, proteomics, metabolomics) can elucidate defense pathways and metabolic reprogramming in response to CNM exposure, offering mechanistic insight and potential biomarkers for risk assessment Environmental Science & Technology.

4.4 Data interpretation, causality, and risk characterization

Given the complexity and variability of CNM-plant interactions, attributing observed effects directly to CNMs versus dissolved ions or co-contaminants requires careful controls, including ionic controls, coated versus uncoated materials, and dissolution measurements. Integrated approaches that combine toxicology with environmental fate data support safer-by-design strategies and regulatory decision-making Environmental Science & Technology, Nanomaterials, Molecules.

5.Implications for risk assessment, regulation, and safe-by-design strategies

5.1 Implications for cosmetic product design

The potential environmental and phytotoxic consequences of CNMs in cosmetics should guide product development toward safer formulations and end-of-life considerations. Safe-by-design principles, including surface modification to reduce toxicity, controlling release profiles, and selecting CNMs with favorable environmental fate characteristics, can mitigate risk while preserving product performance Environmental Science Nano, International Journal of Pharmaceutical Sciences Review and Research, Reference hidden. Lifecycle analyses that incorporate environmental fate endpoints are recommended to inform regulatory submissions and public communication.

5.2 Regulatory and analytical considerations

Regulatory frameworks for nanomaterials in cosmetics vary by jurisdiction, but there is a shared emphasis on safety evaluation, labeling, and environmental risk assessment. The literature highlights the need for standardized analytical methods to detect and quantify CNMs in environmental matrices and cosmetic formulations, as well as explicit guidelines for environmental fate assessments and ecotoxicology testing of CNMs Environmental Science Nano, Journal of Natural Science Research and Review, Molecules. Transparent reporting of physicochemical properties, exposure scenarios, and toxicity endpoints is essential to enable regulatory evaluation and public trust Environmental Science Nano, Journal of Botany, International Journal of Pharmaceutical Sciences Review and Research.

5.3 Research gaps and priorities Key gaps include:

Standardized, environmentally relevant exposure scenarios for CNMs released from cosmetics. Harmonized measurement protocols for CNMs in soils and waters and for plant uptake assays. Mechanistic studies linking CNM physicochemical properties to phytotoxic pathways across diverse plant species. Lifecycle assessment and risk-benefit analyses that integrate environmental fate data with product performance. Safe-by-design strategies incorporating environmental fate considerations during CNM synthesis and functionalization.

6.Case synthesis: representative scenarios and expected outcomes

6.1 Scenario A: Graphene-based CNFs in a cosmetic film applied to soil via biosolid amendments

Hypothesis: Graphene-based CNFs in soil will exhibit limited mobility due to aggregation but could still influence root growth and oxidative stress depending on coating and concentration. Predicted outcomes: Moderate to low phytotoxic effects at low concentrations; dose-dependent increases in ROS and antioxidant responses at higher exposures; potential changes in nutrient uptake profiles.

6.2 Scenario B: GO-derivative nanoparticles in rinse-off products entering aquatic systems

Hypothesis: GO and GO derivatives may exhibit higher phytotoxic potential in hydroponic systems due to dispersion stability and higher bioavailability, with species-specific responses. Predicted outcomes: Inhibition of germination and root elongation in susceptible crops at elevated concentrations; oxidative stress markers elevated; translocation observed in some species.

6.3 Scenario C: CNF/CNT/CGO composites used as cosmetic carriers facilitating slow-release actives

Hypothesis:

Composite CNMs embedded in matrices with controlled release may reduce free CNM bioavailability, mitigating phytotoxicity while delivering cosmetic actives. Predicted outcomes: Attenuated phytotoxic responses relative to free CNMs; material-matrix interactions influence uptake and distribution.

7.Conclusions Environmental fate and phytotoxicity of cosmetic-relevant CNMs are governed by a web of interdependent factors: material identity (graphene, CNTs, CNFs), surface chemistry, dispersion state, exposure media, and plant species. Evidence from environmental science and plant toxicology demonstrates that CNMs can exhibit both beneficial and harmful effects depending on context, underscoring the necessity of comprehensive, standardized assessments throughout the product lifecycle. A safe-by-design approach, informed by robust fate and phytotoxicity data, can enable responsible innovation in nanocosmetics while protecting ecosystems.

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