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Nano-encapsulation in vegetable crops

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Abstract
Nanotechnology is one of the most important technologies of recent years. To fulfill the demands of a growing global population, vegetable crop production and productivity must be increased while utilizing limited resources. Nanotechnology enhances precision farming by reducing inputs like fertilizers, insecticides, fungicides, and herbicides while increasing crop output. Nano encapsulation prevents dangerous compounds from seeping and evaporating, lowering pollution and environmental harm. Nanotechnology has numerous applications in vegetable production, including crop growth, plant protection, genetic modification, and post-harvest. Using nanotechnology can help increase vegetable output sustainably. In this review, we have discussed about the detailed concepts of nanoencapsulation and its process in vegetable crops

Keywords: Nanotechnology, nanoencapsulation, nanoparticles, vegetable crops

1. Introduction

The nano arises from the Greek word "Nanos" meaning dwarf. It denotes a factor of 10-9 or one billionth of meter. Nanotechnology is defined as the creation of functional materials, devices and systems through the control of matter of a scale of 1-100 nm (Singh and Rattanpal, 2014) [14]. Nanotechnology harnesses materials at the nanoscale (typically 1–100 nanometers), where they exhibit unique and valuable properties not observed at larger scales. Nanotechnology is used widely due to,

High Surface Area and High Reactivity: Nanoparticles possess a much larger surface area relative to their volume compared to bulk materials. This increased surface area leads to higher chemical reactivity, enabling faster and more efficient interactions with target molecules (e.g., nutrients, pathogens, or contaminants).

Better Penetration into the Cell: Due to their extremely small size, nanoparticles can move more easily through plant tissues, microbial cell walls, or packaging materials. This allows for more precise delivery of nutrients, agrochemicals, or antimicrobial agents directly into cells, increasing efficacy and minimizing wastage.

Increased Both Plant and Microbial Activities Resulted in More Nutrient Use Efficiency: Nanomaterials can stimulate plant growth and enhance beneficial microbial activity in the soil or plant environment. Improved nutrient delivery and uptake lead to better plant health and yields, while also supporting soil health through enhanced microbial processes, thus maximizing nutrient use efficiency.

Trigger the Enzyme Release: Certain nanoparticles can activate or trigger the release of specific enzymes in plants or microbes. This activation can accelerate essential metabolic processes—such as nutrient assimilation, growth, ripening, or defense responses—tailoring plant or microbial function for better productivity and quality.

Effective Catalyst of Plant/Microbial Metabolism: Due to their unique physical and chemical properties, some nanomaterials act as catalysts, speeding up biochemical reactions in plants or microbes. Enhanced catalytic activity improves processes like photosynthesis, nutrient cycling, decomposition, or even the breakdown of unwanted contaminants, resulting in healthier crops and environments.

2. Nano-encapsulation

Nanoencapsulation is the process of enclosing substances within an inert material in microscopic form at nanoscale scales (Lopez *et al.*, 2006). [8] Protect active compounds such as polyphenols, lipids, enzymes, antioxidants, antimicrobials, and biostimulants from environmental influences (such as oxygen, light, and free radicals) to improve their effectiveness. External stimuli such as pH, enzyme, moisture, and temperature can cause encapsulated substances to be released in a regulated and sustained manner (Mohanta *et al.,* 2019) [10]. Benefits of Nano-encapsulation are (Islam *et al.*, 2022) [7],

1. Provides Stability

Encapsulation enhances the stability of sensitive compounds, improving how they perform and last.

- **Better Processability:** Encapsulated substances are easier to handle during manufacturing and processing, leading to improved efficiency.
- **Enhance Shelf Life:** Encapsulation shields compounds from factors like light, oxygen, and moisture, thereby prolonging the product's usability and freshness.

2. Control Release

This benefit refers to the ability to regulate when and where the encapsulated material is released.

- **Texture Innovation:** Controlled release can modify texture in food products, providing better mouthfeel or innovative textures (e.g., burst-in-mouth effects).
- **Increase Nutritional Value:** Nutrients can be released at specific points (e.g., in the digestive tract), improving the effectiveness of nutritional products.

3. Protect from Environmental Factors

Encapsulation provides a barrier against harmful elements in the environment that may degrade or react with the core material.

1. **Hazardous Compounds:** Encapsulation can trap or isolate potentially dangerous substances to minimize exposure.
2. **Dangerous Chemicals:** It protects active compounds from interacting with harmful chemicals, maintaining their integrity.

4. Helps in Enhancing

Encapsulation contributes to improving the overall effectiveness and functionality of the product.

- **Bio-Efficacy:** The intended action of the active compound (like a drug or nutrient) is more efficiently achieved due to targeted delivery and protection.
- **Bio-Availability:** Encapsulation can improve the absorption of active ingredients in the body, making them more available at the site of action.

3. Methods of encapsulation

3.1. Spray Drying Method

Spray drying is one of the most widely used encapsulation techniques in the food, pharmaceutical, and chemical industries. It involves converting a liquid feed into a dry powder, encapsulating active ingredients in the process (Piñón-Balderrama *et al.*, 2020) [11].

Methods

1. **Feed Preparation & Pumping:** A solution or suspension containing the core material (e.g., flavor, vitamin, drug) and wall material (e.g., maltodextrin, gum arabic) is prepared. This solution is pumped into the drying chamber at a controlled rate. Hot gas (usually air or nitrogen) is introduced to aid the drying process.
2. **Atomization:** The solution is atomized through a nozzle into fine droplets in the drying chamber. This increases surface area, which helps in rapid moisture evaporation.
3. **Drying:** The atomized droplets come into contact with hot drying gas. The moisture evaporates quickly, causing the wall material to encapsulate the core material, forming dry solid particles.
4. **Separation & Collection:** The dried particles are separated from the gas using a cyclone separator. The encapsulated particles are collected, while the exhaust gas is vented out.

Advantages

- Cost-effective and scalable for industrial production
- Rapid drying preserves sensitive compounds
- Produces uniform particle size with good flowability
- Ideal for encapsulating heat-stable materials

Limitations

- Not suitable for heat-sensitive bioactives
- Limited wall material compatibility
- Requires optimization of process parameters

3.2. Freeze Drying Method

Freeze drying, also known as lyophilization, is an advanced encapsulation technique used to preserve heat-sensitive compounds. It works by freezing the material and then reducing the surrounding pressure to allow the frozen water to sublimate directly from solid to gas (Aksoylu Özbek *et al.*, 2021) [1].

Methods

1. **Sample Holder Plate:** The sample holder plate is where the material to be freeze-dried is placed. This material usually contains the core (active ingredient) and wall material (encapsulating agent).
2. **Vacuum Chamber:** The vacuum chamber maintains low pressure during the drying process. It allows the frozen solvent (usually water) to sublimate without passing through the liquid phase.
3. **Freeze-dryer:** The freeze-dryer houses the entire drying process. It controls the freezing, primary drying, and secondary drying stages. It ensures that moisture is removed without applying heat that could degrade sensitive materials.
4. **Condenser:** The condenser traps the water vapor that results from sublimation, turning it back into ice to be removed. It prevents vapor from re-entering the drying chamber.
5. **Vacuum Pump:** The vacuum pump reduces the pressure in the chamber, enabling sublimation. It plays a crucial role in creating the right environment for freeze drying.

Advantages

- Preserves heat-sensitive and delicate compounds
- Maintains original structure and bioactivity
- Results in highly porous and lightweight powders
- Suitable for pharmaceuticals, probiotics, enzymes, etc.

Limitations

- Expensive and time-consuming process
- Requires specialized equipment
- Not suitable for large-scale industrial encapsulation without high investment

3.3. Electrospinning Method

Electrospinning is a nanotechnology-based encapsulation technique used to produce ultrafine fibers from polymer solutions. This method utilizes high voltage to draw charged threads of polymer solution into fibers, which are then collected as nanofiber membranes. It is extensively used in drug delivery, tissue engineering, and food industries (Thakur *et al.*, 2023) [15].

Methods

1. **Syringe Pump:** A syringe pump is used to precisely control the flow rate of the polymer solution, ensuring a consistent feed into the system.
2. **Polymer Solution:** The polymer solution contains both the wall material and the bioactive compound to be encapsulated. It must possess suitable viscosity and conductivity for successful electrospinning.
3. **Spinneret (Metal Needle):** The polymer solution is fed through a spinneret (metal needle), which is connected to a high-voltage power supply. This is where the formation of fibers begins.
4. **High Voltage Power Supply:** High voltage is applied between the spinneret and the collector. This generates an electrostatic field, pulling the polymer solution into fibers.
5. **Taylor Cone:** At the tip of the needle, the solution forms a conical shape called the Taylor cone. When the electrostatic force overcomes surface tension, a thin jet is ejected and stretched into nanofibers.
6. **Collection Roller:** The nanofibers are collected on a grounded roller or flat plate. They form a nonwoven fiber membrane that encapsulates the core material.
7. **Nanofibers (Membrane):** The final product is a mat of nanofibers with embedded bioactive compounds, which can be used in wound dressing, drug delivery systems, or food preservation.

Advantages

- Produces ultrafine fibers with high surface area
- Effective for encapsulating heat-sensitive materials
- Allows for controlled and sustained release of actives
- Versatile range of polymers can be used

Limitations

- Requires precise control of process parameters
- Limited scalability for industrial production
- Sensitive to environmental conditions (temperature, humidity)

4. Applications of nanoencapsules

The applications of Nanoencapsulation are (Salama *et al.*, 2021) [13],

a. Food packaging

Nanocapsules are utilized in food packaging to improve the shelf life and safety of products by incorporating antimicrobial agents or preserving active ingredients.

b. Enhance or hide flavours/aromas

They help in enhancing desirable flavors or masking unwanted tastes and odors in food products, improving consumer acceptance.

c. Bioavailability of nutrients

Nanocapsules can increase the bioavailability of nutrients by protecting them from degradation and enhancing absorption in the body.

d. Micronutrient and antioxidant protection

They safeguard sensitive micronutrients and antioxidants from heat, light, and oxidation, preserving their effectiveness until consumption.

e. Preservants

Nanocapsules serve as carriers for preservatives, allowing controlled and targeted release, thus reducing the amount needed and minimizing side effects.

f. Biosensors

They are used in biosensors to detect pathogens, toxins, or other compounds due to their high sensitivity and specificity.

g. Controlled releases of flavours/aromas

These allow timed or sustained release of flavors and aromas, enhancing the sensory profile of foods.

h. Microbial protection

Nanocapsules protect against microbial contamination by encapsulating antimicrobial agents and releasing them when needed.

5. Uses of nanoencapsulation in agriculture

1. Protection

Nanoencapsulation offers a protective barrier around active ingredients such as pesticides, fertilizers, or bioactive compounds. This encapsulation prevents degradation due to environmental factors like UV light, temperature, and humidity, enhancing product stability and efficacy.

2. Increase Solubility

Many agrochemicals have low water solubility, limiting their absorption and effectiveness. Nanoencapsulation improves the solubility and dispersion of these active ingredients, facilitating better uptake by plants and maximizing agricultural productivity.

3. Reduce the Contact of Active Ingredients with Agricultural Workers

Nanoencapsulation reduces direct exposure of toxic or hazardous agrochemicals to agricultural workers. The encapsulated forms are often safer to handle, minimizing the risks associated with inhalation, skin contact, or accidental ingestion during application.

4. Environment – Reducing Run-off Rates

Encapsulated agrochemicals are released in a controlled manner, reducing excessive application and minimizing chemical run-off into nearby water bodies. This environmentally friendly approach contributes to sustainable farming by decreasing pollution and preserving soil and water quality.

6. Nanoencapsulation release designs

Nanoencapsulation technologies are tailored to deliver active ingredients in a controlled and targeted manner using various release designs. Each method ensures the optimal release of encapsulated materials depending on environmental conditions or stimuli (Salama *et al.*, 2021) [13].

Slow release systems are designed to deliver the encapsulated substance gradually over an extended period. This approach is useful for sustained delivery, such as in pharmaceuticals where a drug must be released slowly within the body or in agriculture for the prolonged effectiveness of nutrients or pesticides.

Quick release designs function by disintegrating upon contact with a specific surface. For example, a capsule may break when it comes into contact with a leaf surface, making it suitable for fast-acting pesticides that must work immediately upon application.

Moisture release mechanisms trigger the release of contents in the presence of water, such as in soil. This method is commonly applied in agriculture to ensure that substances like fertilizers or pesticides are released only when adequate moisture is available, enhancing efficiency and reducing wastage.

Heat release designs are responsive to temperature. They release their content when environmental temperatures rise beyond a certain threshold, making them ideal for temperature-sensitive applications where substance release is triggered by climatic changes.

pH release capsules are designed to respond to specific pH levels. For instance, they may release their contents only under acidic or basic conditions, such as inside a human or plant cell, ensuring targeted delivery within particular biological environments.

Ultrasound release involves rupture of the capsule using external ultrasound frequencies. This non-invasive trigger allows precise control over the timing and location of release, often used in medical or high-tech agricultural applications.

DNA nano capsules serve a unique function by smuggling short strands of foreign DNA into living cells. These are used in genetic engineering and research where precise delivery of genetic material is crucial.

Magnetic release systems incorporate magnetic particles in the capsule shell. When exposed to a magnetic field, the shell ruptures, allowing the content to be released. This method allows remote and controlled activation of release, valuable in both medical and agricultural biotechnology.

7. Nano fertilizers

Nanofertilizers are advanced nutrient carriers engineered at the nanoscale, typically rangingfrom 30 to 40 nanometers. These materials are highly efficient in holding a substantial amount of nutrient ions due to their large surface area. This property allows for a slow and steady release of nutrients, which enhances their availability to plants over an extended period.

One of the key advantages of nanofertilizers is their ability to control the release of nutrients from the fertilizer granules. This controlled release mechanism not only boosts the nutrient use efficiency but also minimizes the loss of nutrients through fixation or leaching into the environment. As a result, plants receive nutrients more effectively while reducing environmental impact (Saidaiah and Geetha, 2021) [12].

In terms of encapsulation of nanostructured nutrients, there are several approaches employed:

1. Nutrients can be encapsulated within nanomaterials such as nanotubes or nanoporous structures, ensuring a protective environment for gradual release.
2. Another approach involves coating nutrients with a thin, protective polymer film that regulates their release over time.
3. Additionally, nutrients may be delivered as nanoparticles or nanoemulsions, ensuring fine dispersion and enhanced uptake by plant systems.

Nano fertilizers are coated with nano materials and improve plant yield through a slow release mechanism. This controlled release process ensures that nutrients are made available to plants over an extended period, increasing their efficiency. The ability of nanofertilizers to hold nutrients more strongly is due to their higher surface tension compared to conventional fertilizers. This enhanced holding capacity means that nutrients are retained longer, reducing the need for frequent applications. Moreover, nano fertilizers have a low environmental impact. By reducing agricultural waste production and minimizing the runoff of nutrients through leaching and volatilization, they help in preventing the pollution of water bodies and soils. This makes nano fertilizers a more sustainable alternative to traditional fertilization methods.

The nano fertilizers can significantly improve plant growth, yield, and fruit quality. For instance, studies have indicated that cucumber plants exhibit improved growth and fruit quality when treated with nano fertilizers, offering a viable alternative to conventional mineral fertilizers (Merghany *et al.*, 2019) [9]. Additionally, the presence of zinc and sulfur nanoparticles has been found to positively affect the growth of broad bean crops at varying concentrations (Ghidan *et al.*, 2020) [6]. This suggests the potential of nano fertilizers to enhance agricultural productivity and sustainability.

Table 1: Nano fertilizers and its application (Bratovcic *et al*., 2021) [3]

Phosphatic nanofertilizers	Increased growth rate (by 32%) and seed yield (by 20%) in soybean
SiO_2 and TiO_2 nanoparticles	Increase the activity of nitrate reductase in soybeans and intensified plant absorption capacity, making its use of water and fertilizer more efficient.
Zinc, manganese nano oxides	The squash plant led to the best vegetative growth characteristics
Iron oxide nanoparticles	Organic matter, protein, lipids, and energy gave the highest value in squash fruits
NPK nanofertilizers	Increased production, profit, and quality in potato
Nanochitosan (Cs) or Carbon Nanotubes (CNTs)	Foliar application improves the growth, yield, and antioxidant system of plants in French bean

8. Nanopesticides

Nanopesticides represent a significant advancement in agricultural technology through the incorporation of engineered nanomaterials with biocidal properties. By using these nanomaterials as active ingredients, nanopesticides can dramatically enhance the bioavailability of pesticides to target pests. This means that the active component is delivered directly and efficiently, with controlled release mechanisms ensuring that it acts precisely where and when it is needed. For example, studies have shown that nano-silica particles can boost tomato yields by effectively controlling pests like the cotton leaf worm (*Spodoptera littoralis*), as evidenced by research from El-bendary and El-Helaly (2013). [5]

The advantages of such formulations are numerous: they promote greater stability of the pesticide, facilitate improved dispersion in water, and crucially, allow for a controlled, slow release of the active compound. This controlled release enhances pest control while reducing the amount and frequency of pesticide applications, which in turn decreases human and environmental exposure to harmful chemicals.

However, the encapsulation used in nanopesticides comes with challenges. Some nutrients may not persist in the soil long enough or may interact with other soil components, leading to unwanted effects. Additionally, the slow-release nature of these formulations can result in the pesticide persisting longer in plants or organisms, which raises new questions about ecological impacts and long-term safety (Saidaiah and Geetha, 2021) [12]. Thus, while nanopesticides offer promising benefits for more sustainable pest management, careful consideration of their behavior in the environment is essential.

Table 2: Polymers used as Nano pesticides (Bratovcic *et al.*, 2021) [3]

Polymers used in nano-encapsulation for nanopesticides and its uses	
Polysaccharides	alginate, carrageenan, xanthan gum, chitosan, modified starch
Proteins	chicken egg albumin, zein, casein, α-lactalbumin, β-lactoglobulin, collagen, gelatine
Coacervates of proteins	Stabilize the protein
Clay nanotubes	Carriers of pesticides for low cost, extended-release and better contact with plants, and they might reduce the amount of pesticides by 70% - 80%
Polylactide nanocomposites	Increase the ion transport and sorption of nutrients
Copper-based (nano) pesticides	Unintended consequences on non-target soil microbial communities, due to their antimicrobial broad spectrum
silica nanomaterials	Improve the growth and yield of crops & modify the plant's catabolism and anabolism

9. Nanoherbicides

Nano-Herbicides control weeds effectively through sustained release and enhanced herbicidal activity. It eliminate adverse environmental effects by reduced leaching as well as negative effects on nontarget plants thus contribute to the improved level of safety in vegetable production (Bratovcic *et al.*, 2021) [3].

10. Nano-fungicides

Nano Fungicides are used when fungal diseases in vegetables causes major loss during production and storage resulting in reduced yields. Silver nanomaterials exhibited strong antifungal property by inactivation of fungal cell wall resulting in disruption of transmembrane and energy metabolism. Used for raising healthy vegetable seedlings through enhanced seed germination and protection from several seed borne and soil borne fungi ((Bratovcic *et al.*, 2021) [3].

11. Nanoencapsulation in seeds

Seeds can also be imbibed with nanoencapsulations with specific bacterial strain termed as Smart seed. Reduce seed rate, ensure right field stand and improved crop performance. Coating seeds with nano membrane, which senses the availability of water and allow seeds to imbibe only when time is right for germination. Aerial broadcasting of seeds embedded with magnetic particle, detect the moisture content during storage to take appropriate measure to reduce the damage. Use of bioanalytical nanosensors to determine ageing of seeds (Bratovcic *et al.*, 2021) [3].

Table 3: Application of Nanoparticles in seeds (Bratovcic *et al.*, 2021) [3]

Carbon nano-tube	Tomato seeds	• CNT carries extensive surface area, they have the potential to regulate the moisture under constraints of irrigation or drought conditions. • Improving the germination (Khodakovskaya, 2009)
ZnO	Tomato, onion, chilli	• Improve the germination and seedling vigor of a wide spectrum
Silver (Ag) nano-particles	Beans, cowpea, watermelon and zucchini	• Due to its anti-microbial and anti-pathogenic effects, seed borne pathogens are effectively controlled and improved germination
TiO_2 Nanoparticle	Fennel	• Favourable effects on seed invigoration. • TiO_2 NPs quench the reactive oxygen species and break the dormancy caused by the phenolics in the seeds.

12. Nanoencapsulation in postharvest management

Nanoencapsulation is a technique that utilizes nanomaterials to enhance the effectiveness, safety, and monitoring of food products after harvest.

1) Nano-sensors

- Nano-sensors are sophisticated devices capable of detecting gases, pathogens, spoilage, and ripeness indicators at the molecular level.

- Their high sensitivity and specificity allow real-time monitoring of storage conditions, ensuring optimal quality and safety of postharvest produce.

2) Nano-coating
- Nano-coating involves the application of edible, ultra-thin layers made from nanoparticles to the surface of fruits, vegetables, or other perishable goods.
- These coatings can extend shelf life by creating barriers to moisture, oxygen, and microbes. They may also deliver natural preservatives or antioxidants directly to the product's surface.

3) Nano-packaging
- Nano-packaging uses nanomaterials to develop packaging films and containers with enhanced properties, such as improved strength, flexibility, and antimicrobial activity.
- Such packaging can better protect food from deterioration, extend shelf life, and sometimes even indicate spoilage via color changes or other signals.

12.1. Nanopackaging
- Vegetables are highly perishable hence post-harvest management is important to increase shelf life and to maintain quality.
- The nanomaterials with other preservation treatments can have a synergistic effect in prolonging shelf life of harvested products (de Sousa *et al.*, 2023) [4].

Different types of nanopackaging (Anvar *et al.*, 2021) [2],

a. Improved Packaging
It enhance the basic protective functions of traditional packaging. Acts as a strong gas barrier to control the exchange of gases like oxygen and carbon dioxide, thereby reducing oxidation and spoilage. Provides temperature resistance, helping products withstand fluctuations in temperature during transport or storage. Ensures humidity resistance, protecting food from moisture that can accelerate spoilage. Other enhancements as required for specific foods (e.g., strength, flexibility, etc.). Mainly focuses on improving the physical and chemical characteristics of packaging materials.

b. Active Packaging
It interact with the food or the environment to actively extend shelf life and improve safety. Inactivation of pathogens, reducing microbial contamination through embedded antimicrobial agents. Expanding the shelf life of products by slowing down spoilage mechanisms. Increasing food safety by minimizing risks associated with bacteria, fungi, and other harmful microorganisms. Moves beyond protection, actively participating in preservation and safety enhancement of food.

c. Intelligent Packaging
It provide real-time information and monitoring capabilities for food quality and safety. Recognition of spoilage by detecting biochemical changes, often using colorimetric indicators or sensors. Detection of pathogens, enabling rapid identification of contamination before consumption. Monitoring food quality, such as freshness, ripeness, or storage conditions, often with the help of embedded nano-sensors. Offers advanced diagnostics, enabling better decision-making regarding food consumption and distribution, thus reducing waste and improving consumer safety.

Table 4: Application of Nano particles in Nano packaging (Bratovcic *et al*., 2021) [3]

Polylactic acid + Montmorillonites (MMT)	Increase thermal resistance
Polyvinylchloride + MMT	Improve optical resistance
Polyethylene + MMT/SiO_2	Improve durability
Polyamide + multiwalled carbon nanotubes	Significant flame resistance
Nanofibres	Barrier and mechanical properties, it also displayed high transparency properties
Silica nanoparticles	Improve mechanical or barrier properties of composites
Starch nanocrystals	Mechanical properties
TiO_2 nanoparticle	Block UV light and provide a longer shelf-life for food
Polylactic acid + ZnO nanoparticle	Highly suitable interaction material for food packing with increased functionality (Martinez-Bueno *et al.*, 2017)
Nano-chitosan and Nano-cellulose	an increase in tensile power, elongation to breakage, clearance and food protection characteristics (Noorbakhsh-Soltani *et al.*,2018)
Nano-Cu	Spraying 0.5ml/L before the packaging prolong the shelf life
Nano biofilm	Prevent the spoilage of vegetables after harvest as they have antioxidant and antimicrobial properties
Nano chitosan	Avoid decay of cucumber and other vegetables

13. Conclusion
Nano technology is the advanced technology used to improve the productivity. The nanotechnology-based delivery of nanoparticles gives promising results for plant disease and pest resistance and enhanced plant growth with the help of controlled release formulations of nanoparticles and increasing the ability of plant to absorb nutrients. Nano materials with micronutrients such as Cu, Zn and Ag favor for the activation of enzymes and the synthesis of biomolecules involved in plant defense. It play an important role in increasing the shelf life of highly perishable nature of vegetables.

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