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Engineering macroalgal nanocarriers for targeted bioactive delivery against agricultural pollutants

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INTRODUCTION & OBJECTIVES

- Pathogen resistance and prohibitions on synthetic inputs dare agricultural disease control, **raising environmental and health concerns.**
- **Macroalgae-derived biodegradable nanocarriers (Bio-MACs)** such as alginic acids, chitosans, and carrageenans provide **sustainable delivery systems.**
- **Bio-MACs** enable **encapsulation** and **controlled release** of antifungal, antibacterial, and biostimulant metabolites.
- These systems protect actives from **degradation, extend soil efficacy,** and **reduce application** rates by up to 40%.
- Bio-MACs show low toxicity to non-target species (*Daphnia magna, Eisenia fetida*) per OECD TG 202/207 guidelines.
- Their **GRAS status** and **biodegradability** support regulatory acceptance in agri-food sectors.
- The biopesticide sector is expanding quickly, with forecasts indicating it will reach USD 10 billion by 2027, underscoring the financial viability of **Bio-MACs.**
- Market adoption requires addressing **nanotechnology concerns, standardizing production,** and **conducting field trials.**

This study aims to explore **the potential of Bio-MACs** for **encapsulating** and **releasing biological metabolite activities.**

Bio-MACs DELIVERY MECHANISM

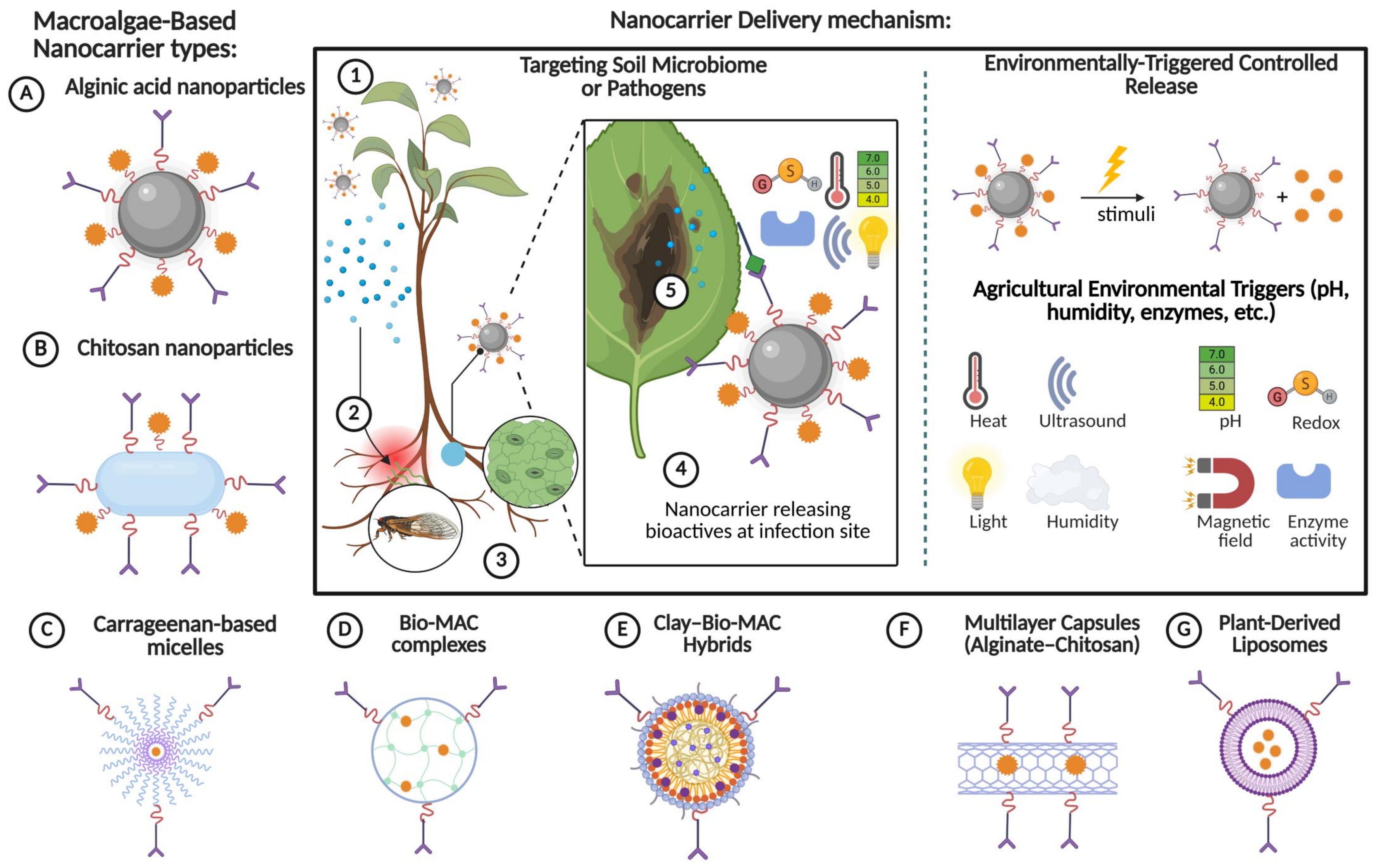

Figure 1: Illustration of types of macroalgae-based nanocarriers and their delivery mechanisms.

Encapsulated nanoparticles (NPs) enter plants through two routes: (1) the **apoplastic route** and (2) the **symplastic route.** In the **apoplastic route,** NPs move along the outer surface of cell membranes and **pass through extracellular spaces, cell walls,** and **xylem vessels. Sympathetic transport,** on the other hand, **takes place along plasmodesmata and cribriform plates, allowing flow between the cytoplasms of adjacent cells.** The apoplastic pathway is integral to radial movement as it enables access to the central root cylinder and vascular tissues. However, sympathetic transport is impeded by Caspary's fringe. After application, NPSs follow a series of coordinated steps (**Figure 1**):

1) **Application:** Nanocarriers with metabolites delivered to the soil or plant through root application or foliar spraying.

2) **Transport:** Once inside the plant, the nanocarriers self-assemble and move toward the target site via the **apoplastic** or **symplastic** route, based on how they were applied (roots or leaves).

3) **Recognition:** They sense environmental cues such as pH levels, enzyme activity, or temperature, which triggers their movement and release mechanism.

4) **Release:** After detecting environmental stimuli, bioactive agents are precisely delivered to the affected area.

5) **Action:** They either interact with pathogens or the microbiome to improve plant health or protect against infection.

LOADING ACTIVE METABOLITES INTO NANOPARTICLES

NPs SYSTEM

During NP formation (incorporation) — **Higher** efficiency (e.g., matrix)

After NP formation (incubation) — **Lower** efficiency (e.g., surface)

LOADING OUTCOME
- Matrix embedding
- Surface adherence

FACTORS INFLUENCING LOADING EFFICIENCY
- Precise of preparation method
- Degree of incorporation
- Physico-chemical properties
- Process parameters (e.g., additives presence and agitation intensity)

LOADING STRATEGIES
- Coacervation
- Iontropic gelation
- Emulsion / evaporation
- Covalent bonding
- Physical adsorption

DEPENDING ON
- Nature of the active metabolite
- Desired release profile
- Intended application

PLANT TOXICITY FROM NANOPARTICLE TRANSPORT IN AGRICULTURAL SYSTEMS

EFFECTS ON PLANTS AND SOIL

At low concentrations
- ↑ Enhancement of **photosynthesis**
- ↑ Nutrient absorption
- ↑ Stress tolerance

At high concentrations
- ↓ Oxidative stress
- Inhibition of germination
- ↓ Reduction of root growth
- ↓ Lower chlorophyll content

CONCLUSION AND FUTURE OUTLOOK

Bio-MACs are a **revolutionary** option to synthetic pesticides, combining improved **effectiveness with reduced risks**

Major **gaps** in knowledge remain, notably on the detailed **molecular mechanisms, degradation** in the environment and **bioaccumulation** of NPs

Targeted regulation and long-term studies are needed to precisely evaluate **nanotoxicity** and guarantee **safe** and **cost-effective** use in agriculture

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