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Sustainable Valorization of Grape Pomace via Liposomal Nanoencapsulation of Phenolic Compounds

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Abstract

- The wine industry generates substantial quantities of agricultural waste, including grape pomace, a residue rich in ***phenolic compounds*** with recognized antioxidant properties.
- This study explores the valorization of grape pomace through ***liposomal nanoencapsulation*** within a circular bioeconomy framework.
- Empty liposomes exhibited a stable nanoscale size of 144 nm, while loaded liposomes displayed a larger, more ***heterogeneous size distribution***, with an encapsulation efficiency of approximately **10%.**

Introduction

- Winemaking leaves behind large volumes of solid residue, chiefly grape pomace, a by-product still ***rich in polyphenolic antioxidants*** that are too often discarded rather than recovered.
- Turning this waste stream into a usable resource fits within ***circular-bioeconomy*** thinking and current sustainable-development priorities.
- Encapsulating such fragile bioactives inside lipid-based nanocarriers is one way to shield them from degradation and improve their **bi*oavailability***.

Materials and Methods

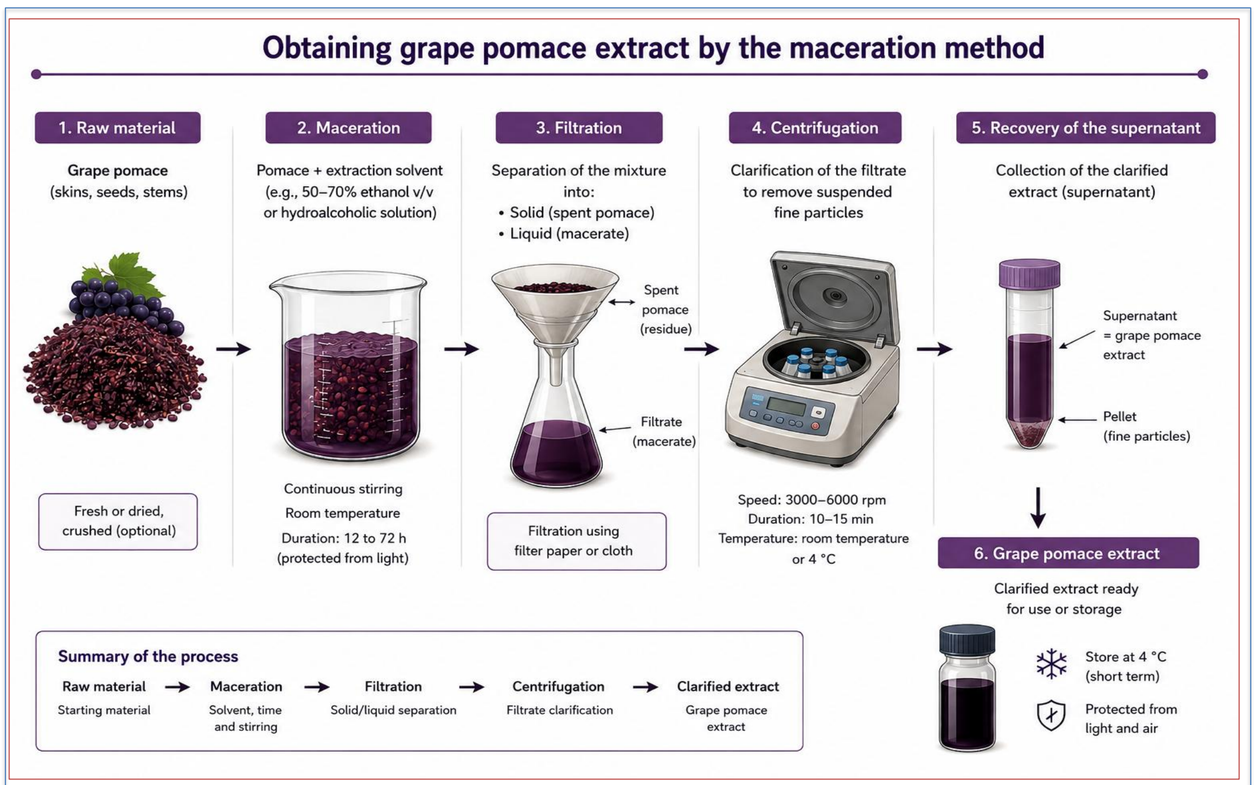

Fig. 1 — Grape pomace extraction process

Flowchart detailing the sequential steps of maceration, filtration, and centrifugation required to obtain and preserve a clarified grape pomace extract (Fig. 1).

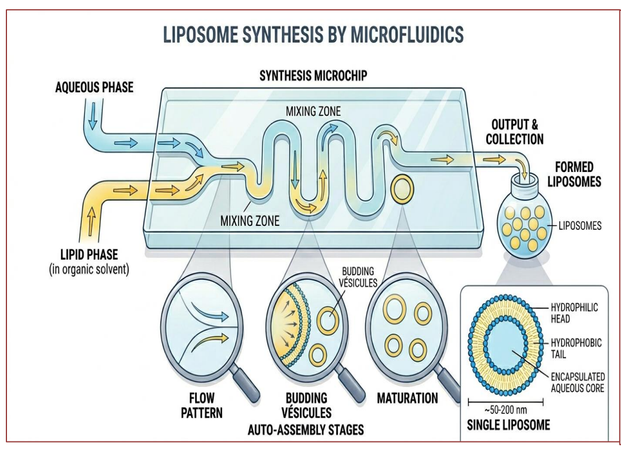

Fig. 2 — Liposome synthesis by microfluidics

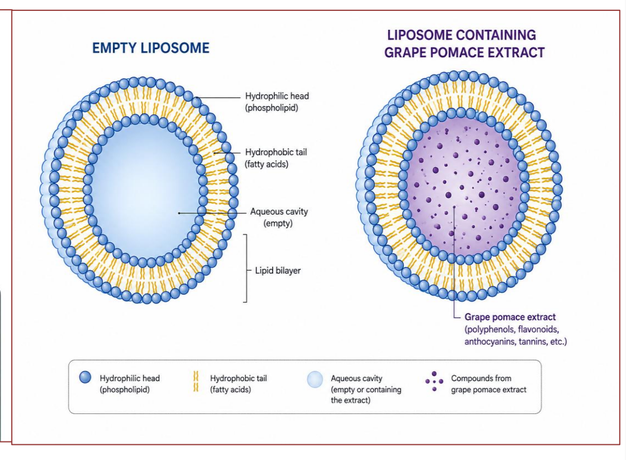

Fig. 3 — Empty vs. loaded liposome structure

Vesicles self-assemble and mature via microfluidics at the aqueous–lipid interface, forming a phospholipid bilayer that encapsulates bioactive compounds (polyphenols, flavonoids, anthocyanins) from the grape pomace extract (Fig.2) as shown by the structural comparison between empty and loaded liposomes (Fig.3).

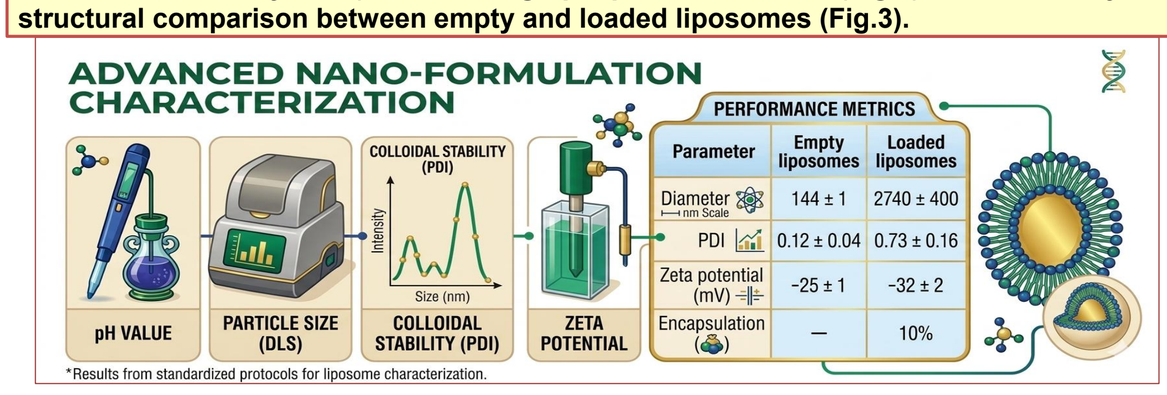

Fig. 4 — Characterization summary

Diagram of the key steps and physicochemical characterization techniques (pH, size by DLS, PDI, and zeta potential) used to compare the performance metrics of empty and loaded liposomes (Fig.4).

Results

Physicochemical Characterization of Liposomes:

- Significant increase in **particle size**: 144 nm → 2740 ± 400 nm after extract loading.
- Broader **size distribution** (PDI: 0.73 ± 0.16), suggesting polydisperse system requiring optimization.
- **Zeta potential** shifted to −32 ± 2 mV, confirming negative surface charge. (Fig. 5)
- **Encapsulation efficiency** of 10% confirms successful incorporation of phenolic compounds.

Comparative Characterization Table

The following table presents a comparison of the main characteristics between empty liposomes and loaded liposomes.

Parameter	Empty liposomes	Loaded liposomes
Diameter (nm)	144 ± 1	2740 ± 400
PDI	0.12 ± 0.04	0.73 ± 0.16
Zeta potential (mV)	−25 ± 1	−32 ± 2
Encapsulation efficiency	—	10%

The encapsulation of the extract into liposomes increased their size and heterogeneity while maintaining good surface stability.

In contrast to empty liposomes (144 nm, PDI 0.12), loaded liposomes showed a marked increase in size and polydispersity, suggesting interactions between phenolic compounds and the lipid bilayer, as well illustrated by the curves below.

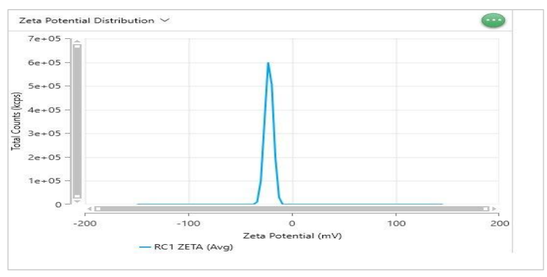

Fig. 5 Zeta potential — Empty liposomes (−25 ± 1 mV)

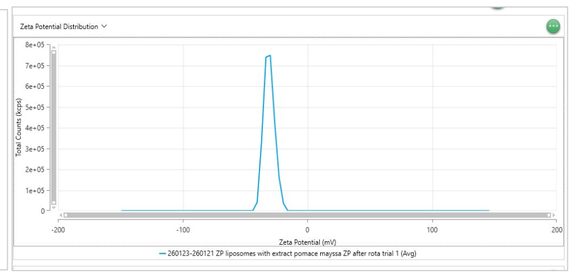

Fig. 6 Zeta potential — Loaded liposomes (−32 ± 2 mV)

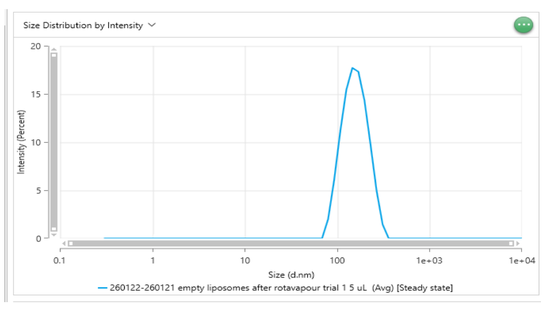

Fig.7 Size distribution — Empty liposomes (PDI 0.12)

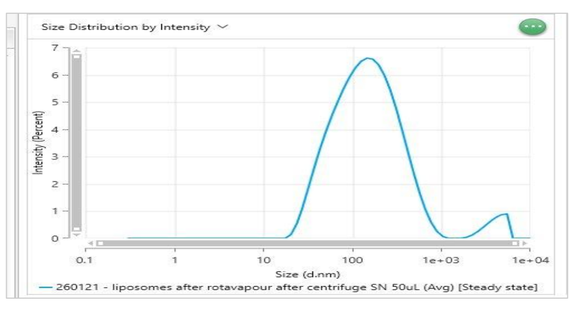

Fig.8 Size distribution — Loaded liposomes (PDI 0.73)

Monodisperse population

Polydisperse population

Discussion

- The preparation **of stable empty liposomes (144 nm, PDI 0.12)** confirms the reliability of the **microfluidic approach** under the selected Sunshine conditions.
- The particle size enlargement upon extract loading **(144 nm → 2740 nm)** suggests interactions between phenolic compounds and lipid bilayers, due to high extract concentration or insufficient pre-treatment.
- Further **optimization of formulation parameters** (extract concentration, lipid composition, FRR, TFR) is required to achieve a narrower size distribution.
- The **10%** encapsulation efficiency highlights the potential for improvement through **pre-treatment of the extract** and **process parameter optimization.**

Conclusion

- This study demonstrates the ***feasibility of encapsulating*** grape pomace phenolic extract into liposomal nanocarriers using a microfluidic system.
- The results highlight the ***potential of grape pomace*** as a valuable bioresource for ***sustainable valorization*** of agro-industrial by-products.
- Further *optimization* is required to improve particle ***size distribution*** and ***encapsulation efficiency*** for future biomedical and cosmetic applications.

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