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Advanced Liposomal CoQ10 Formulation by WBCIL: A Step Forward in Cardiovascular Nutraceutical Therapy

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Abstract
Coenzyme Q10 (CoQ10), or ubiquinone, is a lipid-soluble molecule essential for mitochondrial electron transport and cellular energy production. Its oral bioavailability is limited due to high molecular weight and hydrophobicity. West Bengal Chemical Industries Ltd. (WBCIL), Kolkata, India, addressed this by formulating a liposomal CoQ10 using 75% sunflower-derived phosphatidylcholine.
This study comprehensively characterizes the liposomal CoQ10 in terms of physicochemical properties, encapsulation efficiency (EE%), stability, and controlled release. Analytical methods including High Performance Liquid Chromatography (HPLC), Fourier Transform Infrared (FTIR) Spectroscopy, X-ray Photoelectron Spectroscopy (XPS), Dynamic Light Scattering (DLS), Scanning Electron Microscopy (SEM), and thermal profiling confirmed structural integrity, particle uniformity, and enhanced encapsulation.
For liposome characterisation, HPLC, FTIR, XPS, DLS, SEM, and thermal profiling confirmed structural integrity, particle uniformity, and enhanced encapsulation. HPLC showed 82.05% phosphatidylcholine and 10.82% phosphatidylethanolamine (93% total phospholipids). FTIR confirmed functional groups with C=O (~1738 cm $^{-1}$), CH (~2853, ~2920 cm $^{-1}$), and –OH (3138–3320 cm $^{-1}$). XPS showed a surface composition of C (81.14%), O (17.61%), and P (1.25%).
For Liposomal CoQ10, EE% was 81.51%, surpassing the 70% benchmark. Accelerated stability (40°C ± 2°C, 75% ± 5% RH) showed EE% remained above 81% over six months. Thermal testing (105°C for 4 hours) confirmed structural integrity, supported by DSC analysis. DLS showed particle sizes of 133.9 nm (PDI: 0.294) and 150.2 nm (PDI: 0.3286), with zeta potentials of –31.87 mV and –37.21 mV, indicating good colloidal stability. SEM confirmed smooth, spherical vesicles.
These findings validate WBCIL's liposomal CoQ10 as a highly stable, bioavailable, and effective alternative to conventional CoQ10 supplements.

Keywords
Liposomal CoQ10, Bioavailability, Phosphatidylcholine, Mitochondrial Health, Antioxidant, Nutraceutical Delivery

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I. Introduction

Coenzyme Q10 (CoQ10), also known as ubiquinone, is a lipophilic benzoquinone compound that plays a crucial role in mitochondrial electron transport and ATP synthesis (Littarru & Tiano, 2007). It is ubiquitously present in human tissues, particularly in high-energy-demanding organs such as the heart, liver, and kidneys. Beyond its vital role in energy metabolism, CoQ10 functions as a powerful lipid-soluble antioxidant, protecting cellular membranes from oxidative damage and regenerating other antioxidants such as Vitamin E (Bentinger et al., 2007). Its multifaceted therapeutic potential has led to widespread use in managing cardiovascular diseases, neurodegenerative disorders, diabetes, and age-related conditions (Bhagavan & Chopra, 2006).

Despite its clinical benefits, CoQ10's utility is significantly hindered by its poor oral bioavailability. Its hydrophobic nature, high molecular weight, and limited aqueous solubility result in inefficient gastrointestinal absorption (Bank et al., 2011). Conventional CoQ10 formulations often require high doses to achieve therapeutic plasma concentrations, which can increase the risk of gastrointestinal discomfort and reduce patient compliance. Therefore, innovative delivery systems are essential to overcome these pharmacokinetic limitations and enhance CoQ10's systemic availability (Zhang et al., 2016).

Liposomal technology presents a promising strategy to address these challenges. Liposomes are spherical vesicles composed of phospholipid bilayers that mimic biological membranes. They provide a biocompatible and efficient carrier system for both hydrophilic and lipophilic drugs, facilitating improved solubility, stability, and cellular uptake (Mozafari, 2005). When CoQ10 is encapsulated within liposomes, it becomes more dispersible in aqueous environments and better protected from degradation, allowing for improved absorption and bioavailability (Pavoni et al., 2019).

Table 1: Selected Clinical Studies on Enhanced Bioavailability of Liposomal CoQ10 Formulations

Study	Design	Formulation Type	Sample Size / Population	Key Findings
Lopez-Lluch et al. (2019)	Randomized, double-blind, crossover	Liposomal CoQ10	14 healthy volunteers	Liposomal formulation showed significantly higher plasma CoQ10 levels than powder-based forms
Madhavi et al. (2017)	Open-label, parallel-group	Ubiquinone vs CoQ10 softgel	60 healthy subjects	Ubiquinone provided better bioavailability; suggested use for elderly populations
Takami et al. (2020)	Randomized controlled trial	Nano emulsified CoQ10	36 subjects with mild hypertension	Decreased systolic and diastolic blood pressure; higher plasma levels with nano-formulated CoQ10
Keith et al. (2021)	Randomized, double-blind, placebo	Liposomal CoQ10	40 older adults	Improvements in endothelial function and oxidative stress biomarkers
Bhagavan & Chopra (2006) [Review]	Clinical summary report	Multiple formulations	Review of more than 20 studies	Highlights variability in CoQ10 absorption; delivery form significantly affects systemic uptake

Recent clinical investigations have elucidated the role of advanced delivery systems in optimizing the bioavailability and therapeutic efficacy of coenzyme Q10 (CoQ10), a critical cofactor in mitochondrial bioenergetics. Emphasis has been placed on liposomal, nanoemulsified, and solubilized formulations to overcome CoQ10's lipophilic nature and variable absorption. A seminal randomized, double-blind, crossover trial by López-Lluch et al. (2019) (n=14) demonstrated that liposomal CoQ10 significantly elevated plasma concentrations compared to conventional crystalline formulations, highlighting superior absorptive capacity.

In a comparative open-label trial, Madhavi et al. (2017) (n=60) established that ubiquinone, the reduced CoQ10 form, exhibited enhanced bioavailability relative to standard soft gels, with particular relevance for aging populations exhibiting diminished CoQ10 synthesis. Takami et al. (2020) (n=36, randomized controlled trial) further demonstrated that nanoemulsified CoQ10 significantly reduced systolic and diastolic blood pressure in individuals with mild hypertension, paralleled by elevated circulating CoQ10 levels, suggesting cardiovascular benefits. In a rigorous placebo-controlled study, Keith et al. (2021) (n=40) found that liposomal CoQ10 improved endothelial function and attenuated oxidative stress markers in older adults, indicating potential in mitigating vascular aging. A comprehensive meta-analysis by Bhagavan and Chopra (2006) of over 20 trials emphasized formulation-driven variability in CoQ10 absorption, reinforcing the pivotal influence of delivery systems.

Collectively, these studies provide compelling evidence that advanced CoQ10 formulations—liposomal, nanoemulsified, and solubilized—markedly enhance bioavailability and clinical outcomes, offering a robust foundation for therapeutic applications in metabolic and cardiovascular health.

The mentioned works in Table 2 support the use of liposomal CoQ10, similar to the formulation developed by West Bengal Chemical Industries Ltd., Kolkata, India (WBCIL), as a potent nutraceutical intervention for managing oxidative stress, cardiovascular disorders, and age-associated energy deficits.

Table 2: An outline of particle size, zeta potential and encapsulation efficiency of liposomal CoQ10 reported in the literature

Particle Size (nm)	Zeta Potential (mV)	Encapsulation Efficiency (%)	Reference
~180–200	–30.2	85.4	Yang et al., 2017
150–180	–25.6	83.7	Chen et al., 2019
~160	–29.1	86.1	Gokce et al., 2012 (liposomes)
~120	–32.5	93.5	Gokce et al., 2012 (SLNs, for comparison)

Previous studies on liposomal Coenzyme Q10 (CoQ10) formulations report that particle sizes generally range from 150 to 200 nm, which is suitable for efficient cellular uptake and dermal delivery. Yang et al. (2017) formulated long-circulating liposomes with a particle size of approximately 180–200 nm and a zeta potential of –30.2 mV, achieving an encapsulation efficiency of 85.4%. Chen et al. (2019) optimized CoQ10-loaded liposomes using response surface methodology, resulting in a particle size of 150–180 nm, a zeta potential of –25.6 mV, and an encapsulation efficiency of 83.7%. Gokce et al. (2012) demonstrated slightly smaller liposomes (~160 nm) with a zeta potential of –29.1 mV and encapsulation efficiency of 86.1%. They also compared these solid lipid nanoparticles (SLNs), which showed even higher encapsulation efficiency (93.5%) and a more negative zeta potential (–32.5 mV). Collectively, these findings confirm that liposomal CoQ10 formulations exhibit favourable particle size, good colloidal stability, and high encapsulation efficiency, making them effective delivery systems.

The present study focuses on the advanced liposomal CoQ10 formulation developed by WBCIL by using 75% purified sunflower lecithin. The lecithin matrix was rich in phosphatidylcholine (PC), which is known for its membrane-forming and stabilizing properties (Torchilin, 2005). WBCIL, a long-established manufacturer in the pharmaceutical and nutraceutical sectors—has adopted advanced delivery technology to develop its proprietary Liposomal Coenzyme Q10 (CoQ10) formulation. By utilizing non-GMO sunflower-derived phosphatidylcholine and precision nano-encapsulation techniques, WBCIL aims to produce a highly stable, bioavailable, and potent form of CoQ10. This innovation addresses the drawbacks of conventional CoQ10 supplements, offering a more effective and accessible way of administration, which, despite its efficacy, remains invasive, costly, and less convenient for consumers.

With growing global interest in nutraceuticals that support immunity, anti-aging, and enhanced physical performance—especially in light of public health challenges and a shift toward preventive care—liposomal technologies are gaining prominence in both clinical and consumer health markets. This article critically examines WBCIL's Liposomal CoQ10, focusing on its formulation strategy, bioavailability, and comparative benefits as detailed in their product dossier and supported by existing scientific literature.

In one study, researchers evaluated the absorption efficiency of liposomal CoQ10 using an in vitro intestinal absorption model with Caco-2 cell monolayers. Results demonstrated that the liposomal form achieved markedly better absorption than free mineral, with approximately 70% of the encapsulated compound absorbed within four hours. This enhanced uptake is attributed to the liposome's lipid bilayer, which closely mimics the cellular membranes of Caco-2 cells, facilitating more efficient transport across the intestinal barrier.

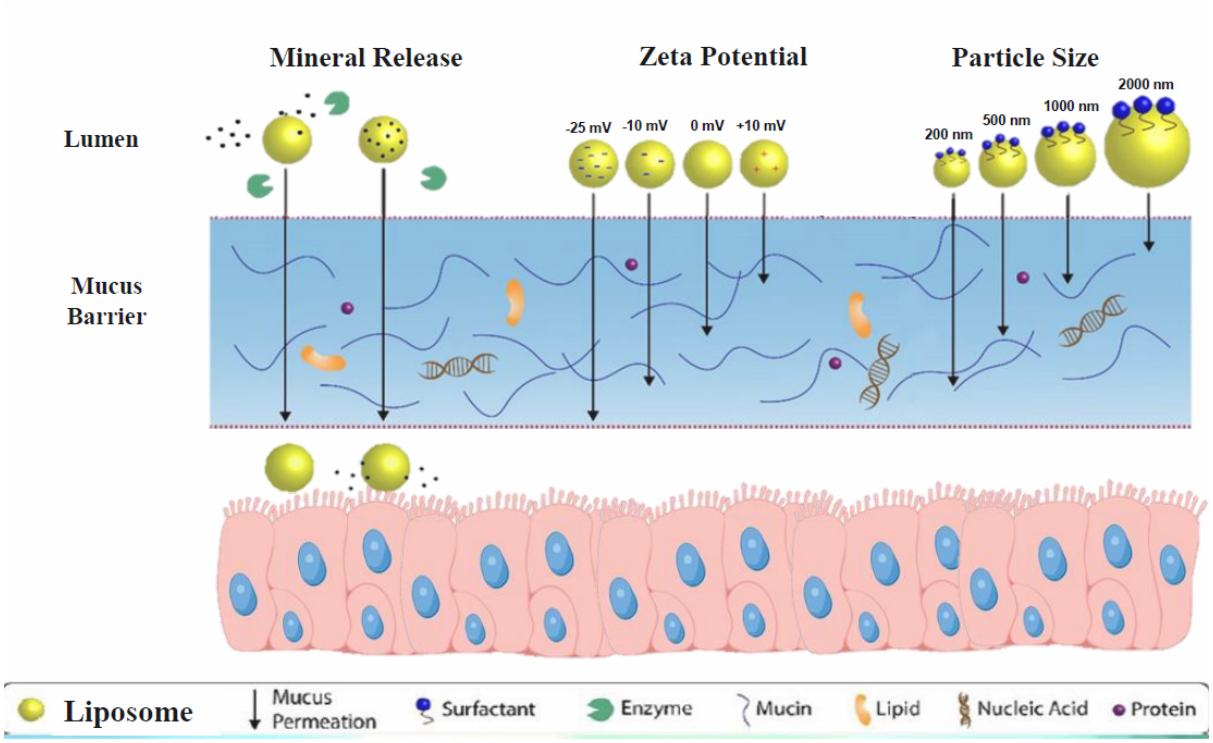

Figure 1: Pictorial Representation of Epidermal CoQ10 Absorption (Adapted from: Haddadzadegan et al., 2022)

The liposomal CoQ10 developed by WBCIL was subjected to a comprehensive series of physicochemical and structural analyses. These included High-Performance Liquid Chromatography (HPLC) for liposome composition analysis, Fourier Transform Infrared Spectroscopy (FTIR) to investigate chemical interactions, X-ray Photoelectron Spectroscopy (XPS) to determine surface composition, Dynamic Light Scattering (DLS) and Zeta Potential analysis to evaluate particle size and dispersion stability, and Scanning Electron Microscopy (SEM) to assess morphology. Encapsulation efficiency was determined using UV-Visible spectrophotometry analysis, while leakage, thermal stability, and endothermic behavior were examined under accelerated conditions and through Differential Scanning Calorimetry (DSC).

This article presents a detailed account of the development and characterization of WBCIL's liposomal CoQ10 formulation. The aim is to demonstrate the formulation's enhanced encapsulation efficiency, superior stability, and improved bioavailability potential, thereby establishing it as a next-generation delivery system for CoQ10 and a model for other hydrophobic nutraceuticals.

Process Flow of 75% Sunflower Lecithin for Liposomal Encapsulation used by WBCIL

The process of preparing 75% sunflower lecithin for liposomal Coenzyme Q10 (CoQ10) encapsulation at WBCIL involves several key stages. Sunflower lecithin, composed of phosphatidylcholine (PC), phosphatidylethanolamine (PE), and other phospholipids, provides the structural components needed for stable nanoscale vesicles. The lecithin is first extracted from sunflower seeds using mechanical cold pressing and aqueous enzymatic extraction, avoiding chemical solvents. It is then purified through centrifugation and filtration to remove impurities. During fractionation, phosphatidylcholine is concentrated to 75% or more using membrane filtration or chromatography. The concentrated lecithin is dried to produce a stable powder. For liposome formation, the lecithin is hydrated with an aqueous CoQ10 solution under controlled conditions, resulting in liposomal vesicles encapsulating the CoQ10. High-pressure homogenization or sonication is used to reduce the size of the vesicles (100–200 nm), improving their bioavailability. Finally, antioxidants such as Vitamin E are added for stability, and the formulation is stored in opaque, air-tight containers to prevent oxidation and light degradation. This process ensures that the liposomal CoQ10 formulation remains potent, stable, and bioavailable, while also aligning with clean-label and allergen-free preferences.

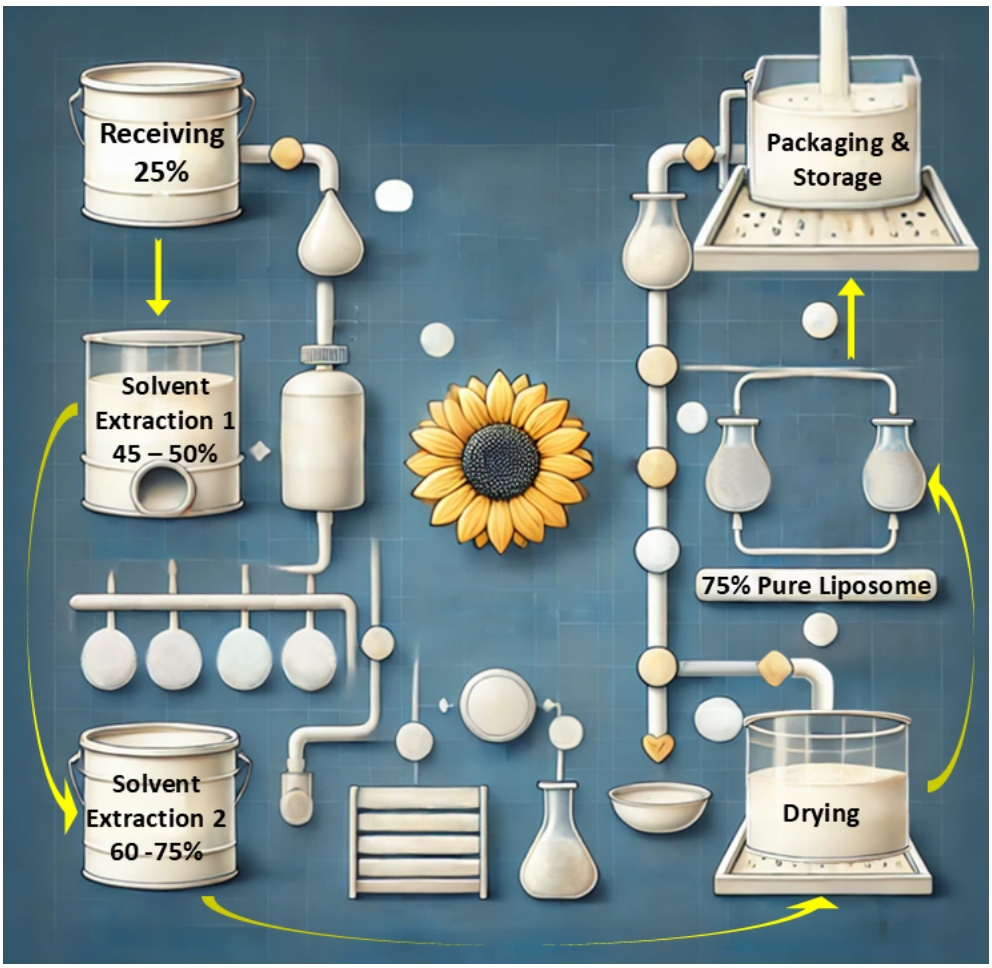

Figure 2: Purification process of Sunflower Lecithin at WBCIL

II. Materials and Methods

2.1. Liposome Characterisation

The characterisation of liposomes is a critical step in evaluating their efficiency, stability, and functionality as a delivery system. In the development of Liposomal CoQ10 by WBCIL, a multi-dimensional analytical approach was undertaken to assess the structural integrity and performance of the liposomes. High Performance Liquid Chromatography (HPLC) was employed to quantitatively confirm the presence of Coenzyme Q10 (CoQ10) within the liposomal matrix by using a C18 column. The mobile phase typically consisted of methanol and water, and detection was performed at 275 nm. This method validated the successful encapsulation of CoQ10 and enabled assessment of any degradation during the formulation process.

Fourier Transform Infrared (FTIR) Spectroscopy was used to investigate the chemical interactions between the phospholipids and CoQ10 within the liposomal system. Spectra were recorded from 4000–500 cm $^{-1}$ using an attenuated total reflectance (ATR) technique, with attention to identifying characteristic CoQ10 functional groups such as C=O, aromatic C=C, and C-H stretching vibrations. Comparative spectra were obtained for CoQ10 API, empty liposomes, and the final liposomal CoQ10 formulation to evaluate encapsulation and structural stability.

X-ray Photoelectron Spectroscopy (XPS) was conducted using PHI 5000 VERSA PROBE III (ULVAC-PHI, USA) at the Central Research Facility, IIT-Kharagpur to analyze the surface elemental composition and bonding environments within the liposomes.

Dynamic Light Scattering (DLS) was conducted at Indian Association for the Cultivation of Science (IACS), Jadavpur using Malvern Zetasizer ZEN 3600 to assess particle size, distribution, and Polydispersity Index (PDI) to evaluate homogeneity, while zeta potential measurements confirmed electrostatic stability, preventing agglomeration. Zeta potential measurements were performed to assess electrostatic stability and the likelihood of particle aggregation, which is crucial for the stability of colloidal systems.

Scanning Electron Microscopy (SEM) was employed to examine the surface morphology and structural integrity of the liposomes. This technique offers high-resolution imaging, enabling detailed visualization of the vesicle architecture and surface features. The analysis was carried out using a Field Emission Gun-Scanning Electron Microscope (Merlin, Gemini II, Zeiss, Germany) at the Central Research Facility, IIT Kharagpur. For sample preparation, the liposomes were placed on an aluminum stub using a conductive adhesive. A thin gold coating was applied using a sputter coater to improve electrical conductivity and enhance image quality (Danaei et al., 2018). The SEM was operated under vacuum conditions, and images were taken at different magnifications to evaluate the shape, uniformity, and distribution of the liposomal vesicles.

2.2. Encapsulation Efficiency

Encapsulation efficiency (EE%) of coenzyme Q10 (CoQ10) within liposomes was quantified to determine the proportion of CoQ10 effectively entrapped relative to the total amount used in formulation. EE% was measured via UV-visible spectrophotometry, employing the formula:

$$\times 100$$

This parameter is pivotal for assessing the performance of liposomal systems in encapsulating hydrophobic molecules like CoQ10, directly influencing delivery efficiency and therapeutic potential. High EE% values indicate robust vesicle integrity and optimized CoQ10 retention, critical for clinical applications.

2.3. Dynamic Light Scattering (DLS) Analysis

DLS was conducted at IACS, Jadavpur using Malvern Zetasizer ZEN 3600 to assess particle size, distribution, and PDI of liposomal CoQ10 formulations. Samples were diluted with distilled water and analyzed using a DLS instrument to assess nanometric sizing and uniformity. This analysis is essential in understanding how the formulation behaves in suspension and its potential for enhanced absorption. The methodology was consistent with nanoparticle characterization protocols by Danaei et al. (2018) and Wagner & Vorauer-Uhl (2011).

2.4. Behavior of Liposomal CoQ10

The zeta potential of the liposomal CoQ10 formulation was measured to evaluate the surface charge and colloidal stability of the vesicles. Zeta potential analysis was performed in liquid medium using DLS Zeta-sizer instrument at IACS, Jadavpur using Malvern Zetasizer ZEN 3600. This analysis was guided by established protocols for liposomal stability outlined by Allen & Cullis (2013) and Mozafari (2005).

2.5. FTIR Spectra of API, Liposome, and Liposomal CoQ10

FTIR spectroscopy was employed to evaluate the molecular interactions and functional group integrity of the active pharmaceutical ingredient (Coenzyme Q10), the pure lecithin liposome, and the liposomal CoQ10 formulation. This technique is essential for confirming the physical entrapment of CoQ10 within the liposomal matrix and verifying the absence of unintended chemical alterations, ensuring the stability of the active compound (Pavoni et al., 2019).

For spectral analysis, samples were prepared using the ATR method. A small amount of each sample—CoQ10 API, empty liposomes, and liposomal CoQ10—were carefully placed on the ATR crystal to ensure consistent contact and spectral quality. Spectra were recorded using an FTIR instrument (Agilent, USA) over the range of 4000–400 cm $^{-1}$, with a resolution of 4 cm $^{-1}$ and 32 scans per sample to enhance the signal-to-noise ratio. A background spectrum was obtained using a clean ATR crystal under the same measurement conditions (Suresh et al., 2020).

Each spectrum was analyzed in detail to identify the shifts in peak positions, broadening, or changes in intensity that indicate molecular interactions between CoQ10 and the lipid bilayer. Special focus was placed on characteristic peaks for O–H, C=O, and P=O functional groups, which serve as key indicators of CoQ10's

integration into the phospholipid structure and the maintenance of its chemical identity during encapsulation (Mozafari, 2005).

2.6. Leakage study

To assess the retention capacity of liposomal CoQ10 and evaluate its formulation stability under physiological and storage conditions, a leakage study was conducted. Liposomal CoQ10 samples were stored at 40°C ± 2°C and a relative humidity of 75% ± 5% for up to six months. At predetermined intervals (0, 1, 2, 3, and 6 months), aliquots were withdrawn, and the encapsulated CoQ10 was separated from free CoQ10 using ultracentrifugation. The supernatant was analyzed using UV-Vis spectroscopy to quantify the amount of CoQ10 that had leaked from the liposomes. Encapsulation efficiency was then recalculated to monitor any degradation or loss over time. This method provides insight into the structural stability of the liposomes and their capacity to retain the active ingredient throughout shelf-life (Liu et al., 2016; Torchilin, 2005).

2.7. Stability study at Elevated Temperatures

To evaluate the resilience of liposomal CoQ10 under thermal stress, temperature stability studies were conducted. Samples of liposomal CoQ10 were exposed to room temperature (RT) and elevated temperature of 105°C for 4 hours. After exposure, samples were analyzed to determine any changes in physical characteristics and chemical stability by measuring assay percentage and encapsulation efficiency percentage via UV-Vis spectroscopy analysis. This thermal exposure test reveals the ability of the lipid bilayer to protect CoQ10 from degradation under extreme conditions, simulating transportation or storage in tropical climates.

2.8. Differential Scanning Calorimetry (DSC) Analysis

The thermal properties of the liposomal CoQ10 sample were analyzed using DSC. This analysis was performed at Sapala Organics (Secunderabad, India). The sample was prepared by placing it in a standard aluminium pan, and an empty aluminium pan was used as the reference. The analysis began at an initial temperature of 40°C, with a constant heating rate of 10°C/min, up to a final temperature of 500°C. The DSC thermogram was recorded to observe melting points, phase transitions, and thermal stability of the sample (Gupta Banerjee et al., 2025).

III. Results and Discussion

3.1. Liposome Characterisation

HPLC analysis revealed that the liposomes containes 82.05% Phosphatidylcholine (PC) and 10.82% Phosphatidylethanolamine (PE), resulting in a high total phospholipid content of 93% (figure-3). This high lipid content is essential for forming a stable bilayer structure capable of efficiently encapsulating lipophilic molecules such as Coenzyme Q10 (CoQ10) (Akbarzadeh et al., 2013; Pavlova et al., 2015). FTIR spectroscopy further validated the structural integrity of the liposomes, with characteristic C=O stretching at ~1738 cm^{-1}, CH vibrations at ~2853 and ~2920 cm^{-1}, and broad –OH stretching bands around 3138–3320 cm^{-1} (Figure-10). These bands signify robust hydrophilic and hydrophobic interactions, both of which are crucial for ensuring stability in aqueous dispersions (Suresh et al., 2020; Mozafari, 2005). Energy Dispersive X-ray Analysis (EDAX) confirmed the elemental surface composition of the liposomes, identifying Carbon (17.81%), Oxygen (45.05%), nitrogen (17.23%), and Phosphorus (19.91%), consistent with the phospholipid-based structure and demonstrating the biocompatibility of the liposomal matrix (Mozafari, 2005) (Figure-5).

DLS analysis showed that liposomes had an average particle size of 133.9 nm with a PDI of 0.294, indicating uniform size distribution. The zeta potential was recorded at -31.87 mV, reflecting strong electrostatic repulsion between particles (Table-3). These values suggest that the liposomal CoQ10 formulation is both physically stable and pharmaceutically suitable for enhanced delivery applications (Danaei et al., 2018; Wagner & Vorauer-Uhl, 2011).

SEM imaging of the liposomes revealed well-formed, spherical vesicles with smooth surfaces (Figure-6). The observed average diameter aligned closely with the size distribution results obtained from DLS. The liposomes exhibited a uniform shape, supporting the efficiency of the lipid hydration technique used in their preparation. Additionally, no notable aggregation was detected, suggesting that the formulation remained stable under the tested experimental conditions.

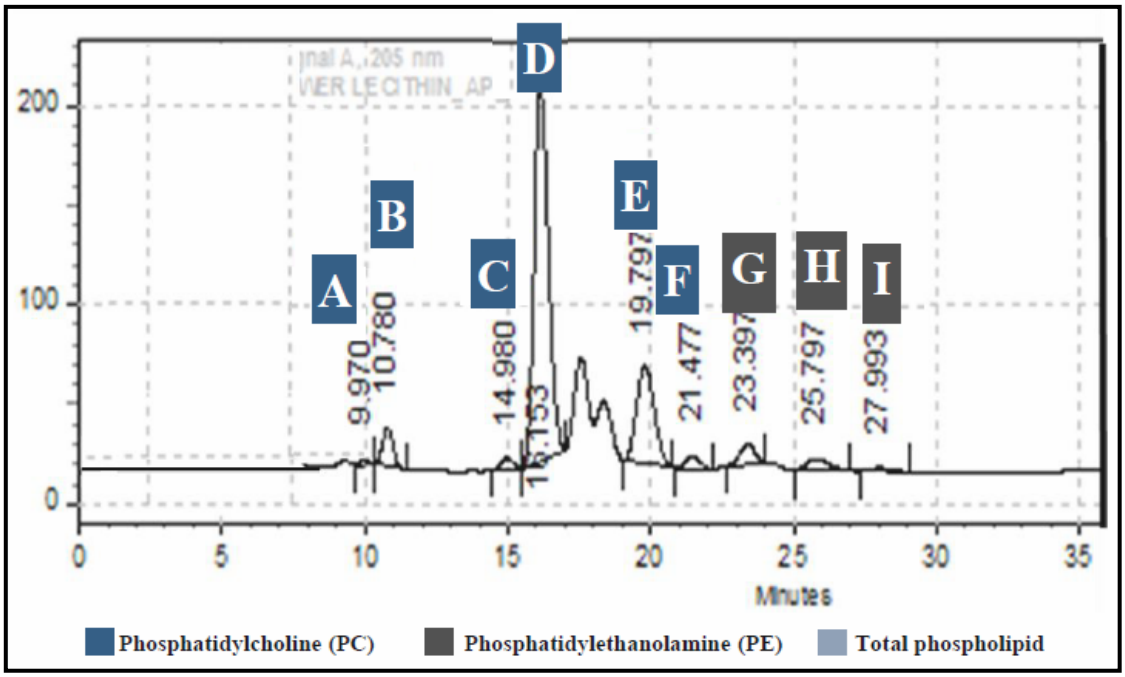

Figure 3: Chromatogram of Liposome with peaks of PC and PE

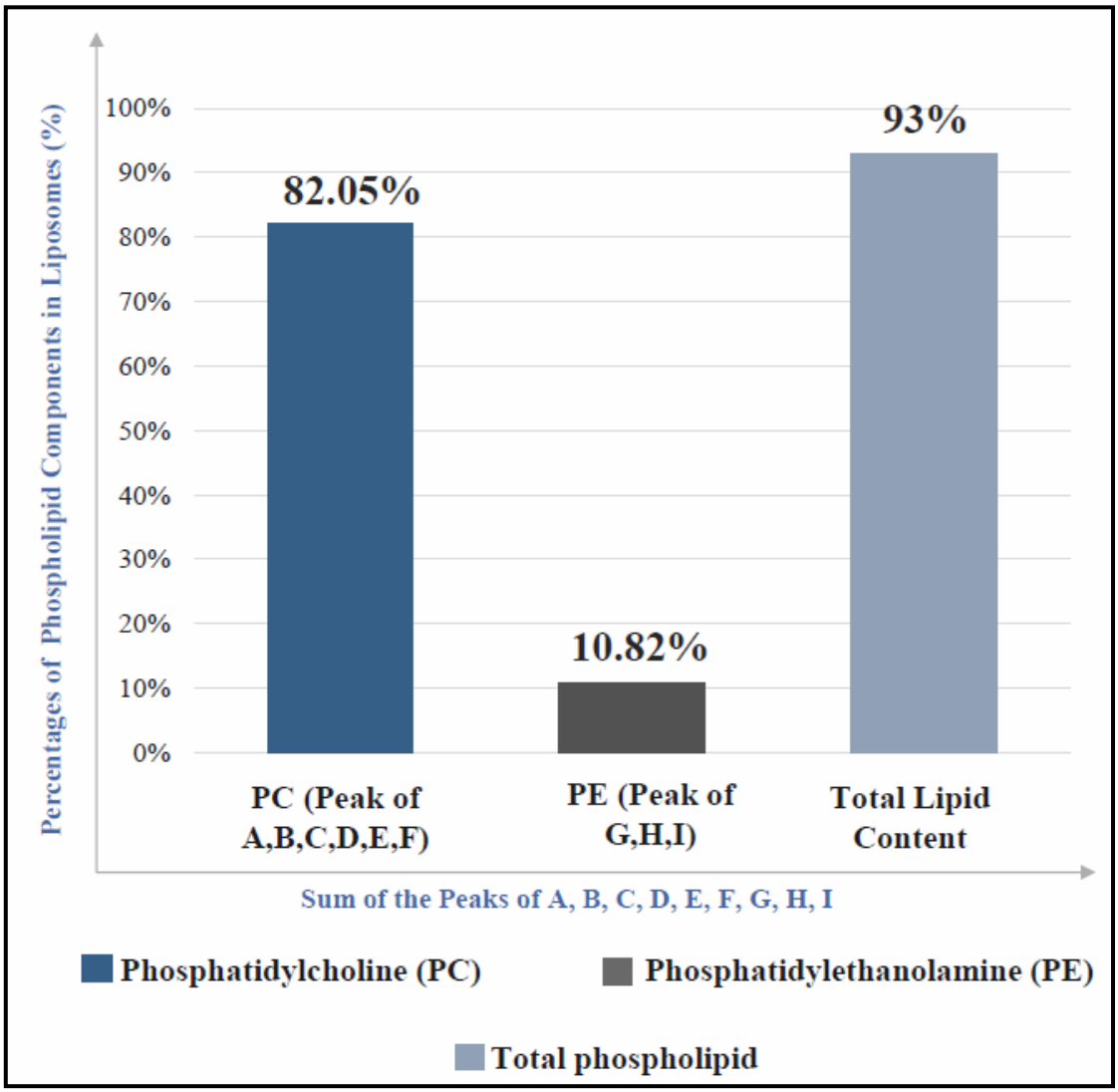

Figure 4: Chart showing composition of Liposomes with 82.05% PC and 10.82% of PE resulting in 93% total phospholipid content

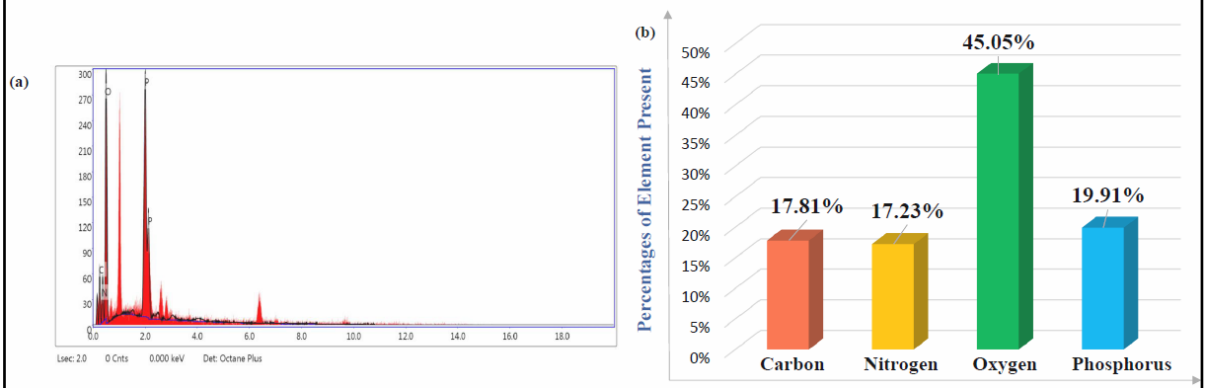

Figure 5: EDAX spectrum of liposomes showing (a) characteristic peaks for carbon (C), nitrogen (N), oxygen (O), and phosphorus (P), confirming the elemental composition typical of phospholipid-based structures. (b) Quantity of elements present in Liposome

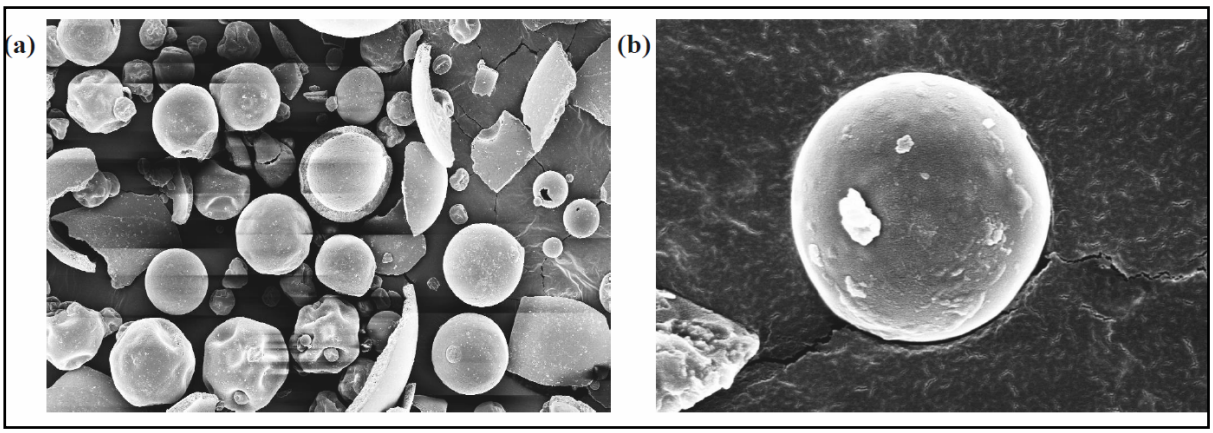

Figure 6: (a) SEM image of Liposomes, (b) Zoomed in view of a Liposome

Table 3: Liposome –Particle Size, Uniformity & Behavior

Particle size	133.9 nm
Polydispersity	0.2946
Zeta potential	-31.87 mv

3.2. Encapsulation Efficiency of Liposomal CoQ10

The encapsulation efficiency (EE) of liposomal CoQ10 was determined by quantifying the amount of free CoQ10 in the supernatant after centrifugation. EE was calculated using the standard formula. The results revealed an encapsulation efficiency of 81.51%, indicating highly effective entrapment of CoQ10 within the liposomal bilayer. This value exceeds the minimum standard (NLT 70%) and highlights the impact of optimal lipid-to-drug ratios on improving encapsulation. Such high efficiency is particularly significant for lipophilic compounds like CoQ10, underscoring the potential of liposomes to protect and enhance the delivery of these molecules (Akbarzadeh et al., 2013; Danaei et al., 2018).

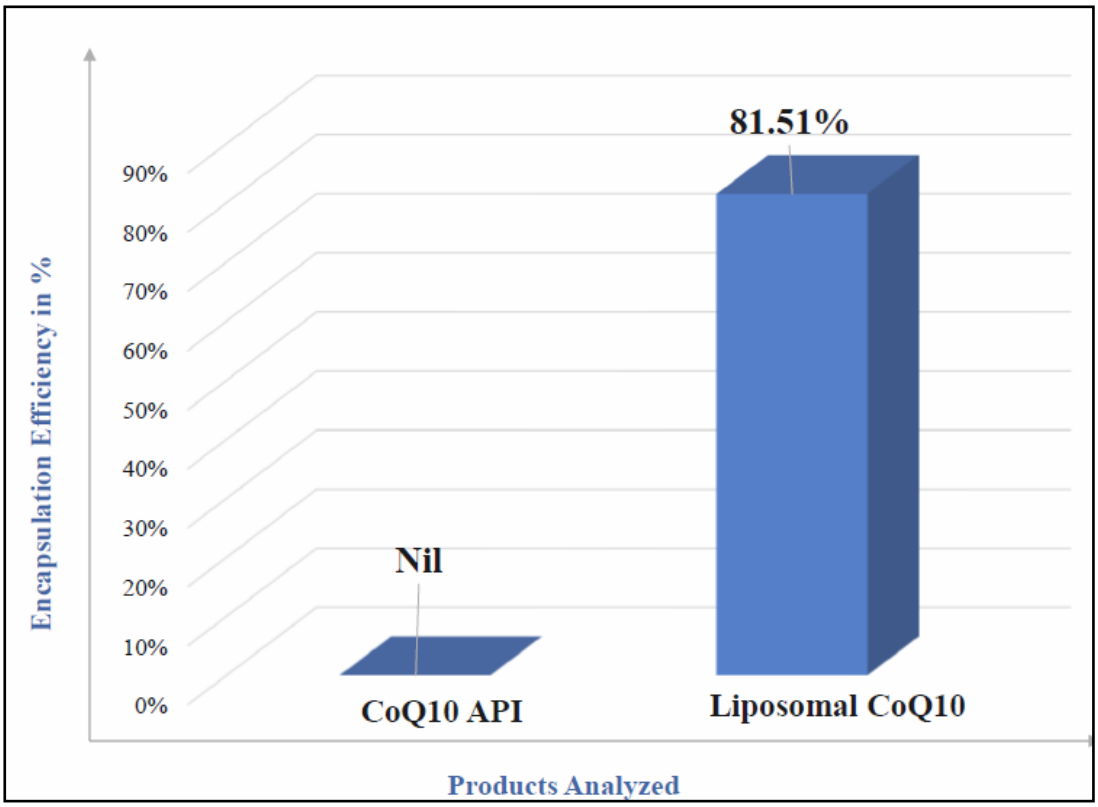

Figure 7: Encapsulation Efficiency determined via validated UV-Vis Spectrophotometry data

3.3. Dynamic Light Scattering (DLS) Analysis

DLS analysis of liposomal CoQ10 demonstrated a mean particle size of 150.2 nm with a PDI of 0.3286, reflecting a moderately narrow size distribution. These values indicate a nanometric and relatively uniform formulation suitable for enhancement of bioavailability. These parameters suggest that the liposomes are capable of remaining dispersed in solution without aggregating, a desirable trait for oral and systemic delivery (Danaei et al., 2018; Wagner & Vorauer-Uhl, 2011).

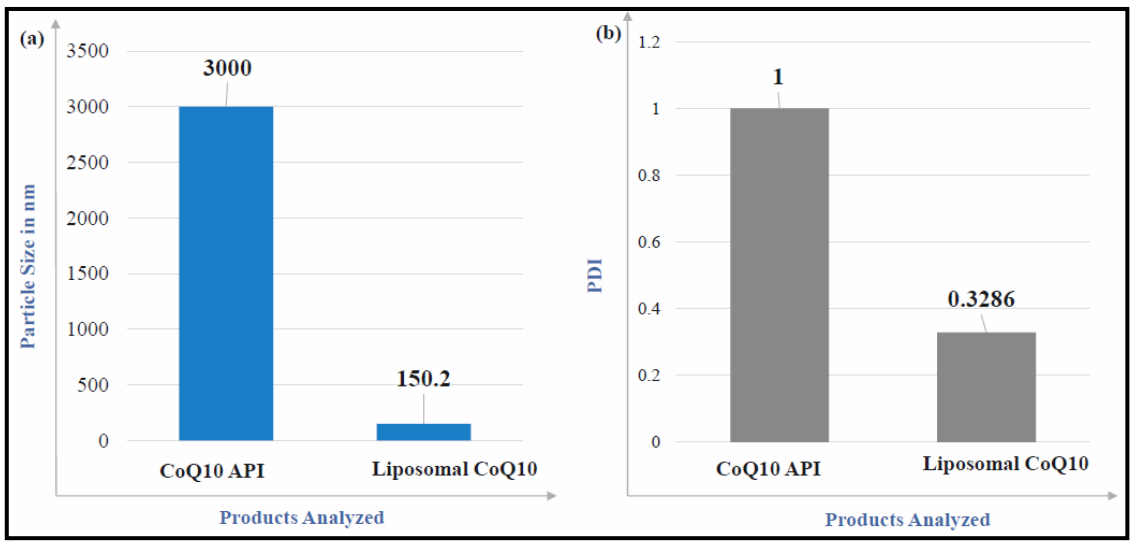

Figure 8: Chart comparing (a) Particle size and (b) PDI between CoQ10 API and liposomal CoQ10

3.4. Surface Charge Properties as Determined by Zeta Potential

The surface charge properties of liposomal CoQ10 were assessed via zeta potential measurements, which reflect the electrostatic stability of colloidal suspensions. The liposomal CoQ10 exhibited a zeta potential of -37.21 mV, compared to -34.06 mV for the CoQ10 API. This more negative value signifies the establishment

of a robust electric double layer around the liposomes, minimizing particle aggregation through electrostatic repulsion. The enhanced stability helps maintain the dispersion quality of the formulation during storage and transportation, contributing to its shelf-life and bioavailability (Allen & Cullis, 2013; Mozafari, 2005).

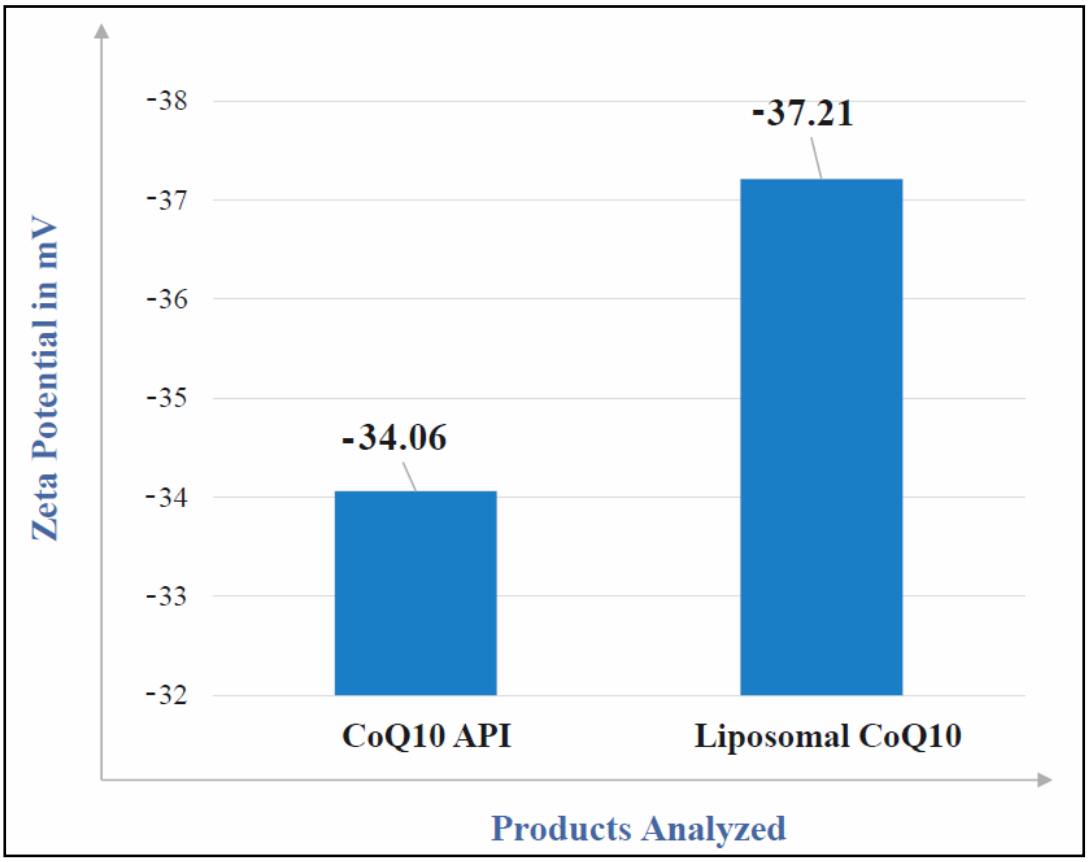

Figure 9: Chart comparing Zeta Potential between CoQ10 API and liposomal CoQ10

3.5. FTIR Spectra of API, Liposome, and Liposomal CoQ10

FTIR spectroscopy was conducted to analyze molecular interactions among CoQ10 API, empty liposome, and liposomal CoQ10. The FTIR spectrum of CoQ10 API displayed prominent peaks at 1655 cm $^{-1}$ (C=O stretching), 1508 cm $^{-1}$ (aromatic C=C), and 2954 cm $^{-1}$ (methyl C–H). In the liposomal CoQ10 formulation, peak at 1655 cm $^{-1}$ confirms the presence of the carbonyl group, while the broad, intense -OH peak around 3400 cm $^{-1}$ indicates sustained release due to hydrogen bonding. These peaks were slightly shifted and broadened, suggesting interactions between the CoQ10 molecules and the phospholipid bilayer. Distinct peaks at 2923 cm $^{-1}$and 2853 cm $^{-1}$correspond to the asymmetric and symmetric stretching vibrations of aliphatic C-H bonds, confirm hydrophobic interactions. The broad peak at 3400 cm $^{-1}$, overlapping with the OH stretch, also reflects hydrophilic interactions due to the presence of polar functional groups or water.

These spectral changes indicate that CoQ10 is successfully encapsulated and stabilized within the liposomal matrix without undergoing chemical degradation. The interaction between the hydrophobic CoQ10 and the lipid tails contributes to the thermodynamic stability of the formulation, while hydrogen bonding between polar head groups and CoQ10 functional groups aids in aqueous dispersion (Pavoni et al., 2019; Suresh et al., 2020).

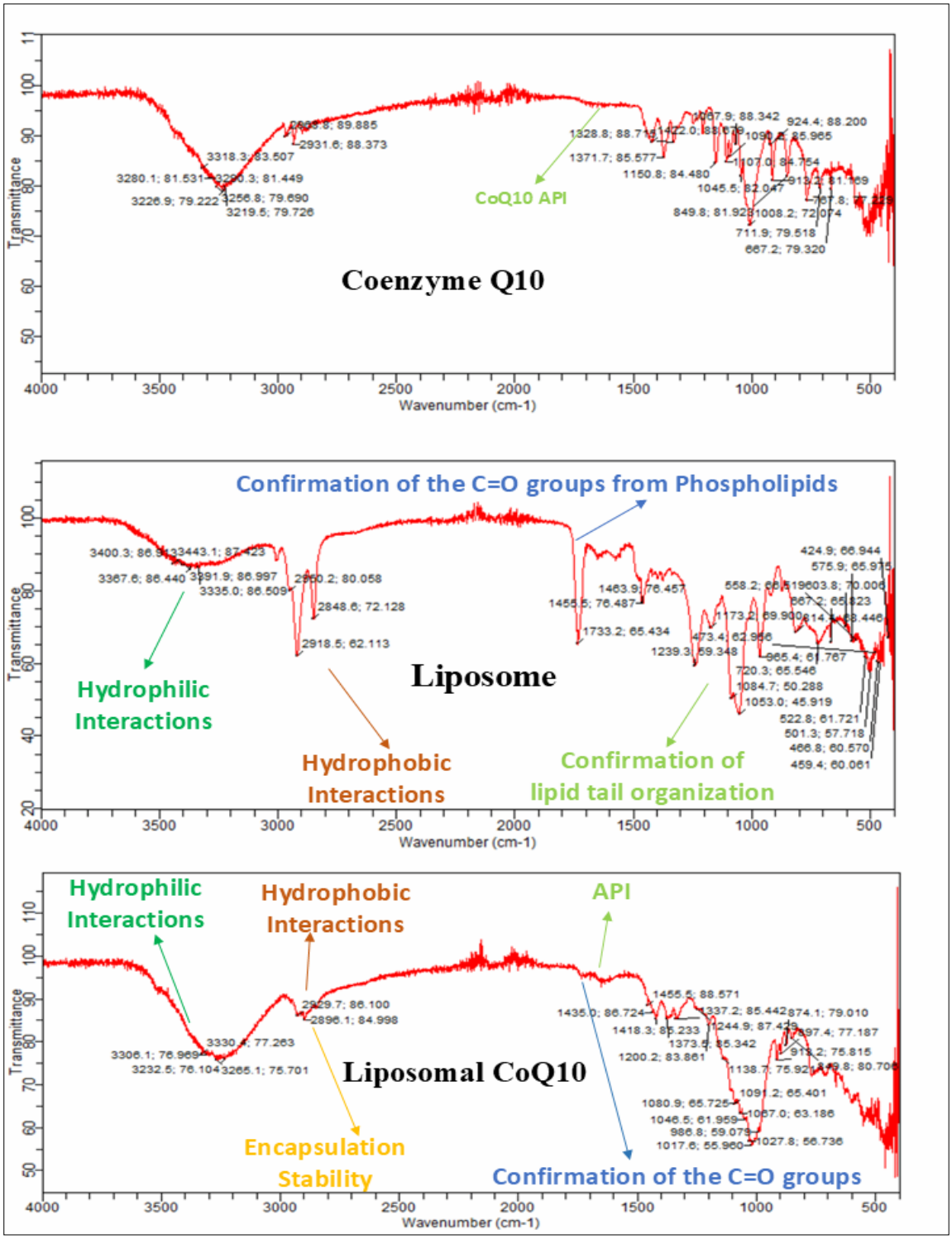

Figure 10: FTIR Transmission spectrum showing bands at different wavelengths of (a) CoQ10 API, (b) Liposome and (c) Liposomal CoQ10

Table 4: Allotment of FTIR peaks in empty liposome, Non-Liposomal CoQ10, and Liposomal CoQ10

Parameter	Empty Liposome	CoQ10 API	Liposomal CoQ10
Confirmation of OH Groups	Broad peak near 3400 cm ¹ (due to lipid hydration)	Broad OH stretch around 3400 cm ¹	Retention of broad OH stretch confirming hydration stability and successful encapsulation
Confirmation of C=O Groups	Peak near 1738 cm ¹ (ester carbonyl from phospholipids)	Strong peak at 1655 cm ¹ (carbonyl group of CoQ10)	Peak shift observed around 1725–1740 cm ¹ indicating interaction between CoQ10 and lipid bilayer
Hydrophobic Interactions	CH symmetric and asymmetric stretches at 2923	Moderate CH stretches (less prominent)	Distinct CH and CH stretches at 2923–2853 cm ¹ confirming lipid tail

	and 2853 cm ¹		alignment around CoQ10
Hydrophilic Interactions	PO stretching at ~1024 cm ¹ confirming headgroup structure	Presence of carbonyl and aromatic bands at ~1655 cm ¹ and 1508 cm ¹	Retained PO and C=O peaks with minor shifts, confirming strong interactions with polar lipid heads
Encapsulation Stability	Stable CH , CH , and phosphate peaks	Intense CoQ10-specific peaks at 1655, 1508, and 2954 cm ¹	Retention and integration of lipid and API peaks validating effective encapsulation
Lipid Tail Organization	Ordered bilayer indicated by CH peaks at 2853–2923 cm ¹	Not applicable	Similar CH peaks with reduced sharpness, indicating structural rearrangement post-CoQ10 encapsulation

3.6. EDAX analysis of liposomal CoQ10

EDAX elemental composition analysis of liposomal CoQ10 shows the distribution of four primary elements—carbon (C), nitrogen (N), oxygen (O), and phosphorus (P)—in the liposomal formulation. Carbon dominates the composition with a significant 54.17%, followed by oxygen at 27.34%, nitrogen at 18.20%, and a minimal amount of phosphorus at 0.28%. The high carbon content is consistent with the organic nature of CoQ10 and its lipid-based encapsulation. Oxygen and nitrogen also contribute substantially, indicative of the presence of oxygen-rich CoQ10 and possible amine groups in stabilizing agents or lipid components. The very low phosphorus content suggests minimal phospholipid concentration or a different formulation base compared to traditional phospholipid liposomes. Complete absence of CoQ10 highlights proper encapsulation property of the formulation.

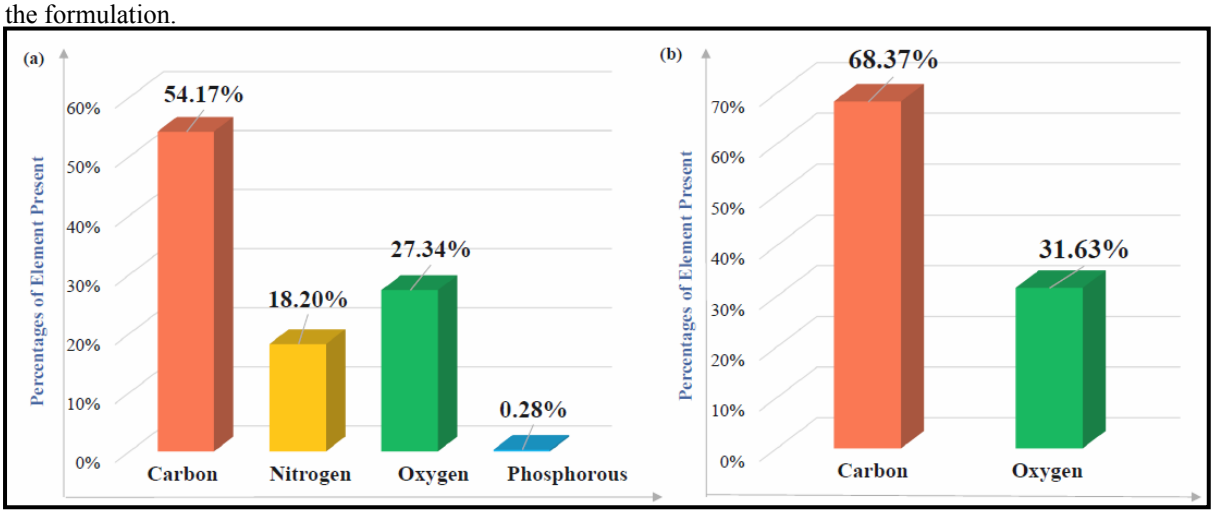

Figure 11: A graphical representation of the percentages of elements composing (a) Liposomal CoQ10 and (b) CoQ10 API

3.7. Leakage of CoQ10 from Liposomes

The initial encapsulation efficiency was recorded at 81.51%. Over the six-month period, EE% values showed minimal variation, remaining consistently above 81% with slight fluctuations (81%, 81.22%, 81.22%, 81%), indicating excellent stability. Similarly, the assay percentage confirmed that the liposomal CoQ10 remained unchanged from 42.56% to 42.33% (1st month), 43% (2nd month), 42.89% (3rd month), and 42.86% (6th month) suggesting no degradation and excellent retention.

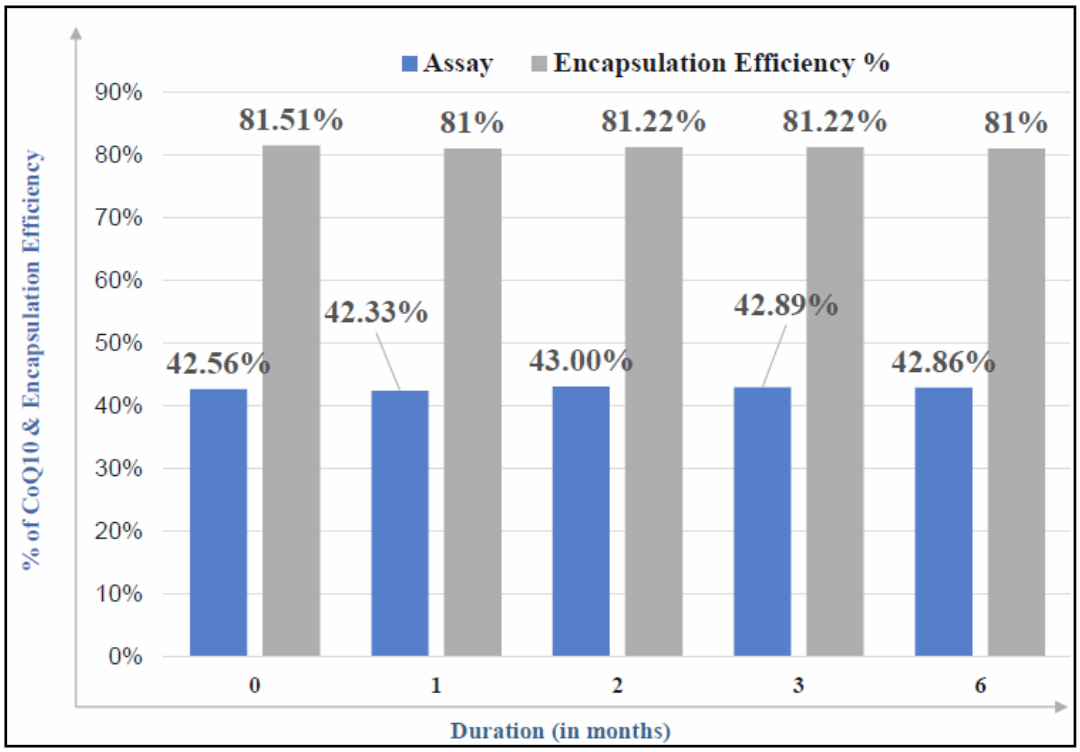

Figure 12: Chart comparing the stability of Liposomal CoQ10 stored over a period of 6 months at 40°C ± 2°C and a relative humidity of 75% ± 5%.

These results demonstrate that the liposomal formulation significantly enhances the stability and retention of CoQ10 under stress storage conditions, making it a viable delivery system for long-term applications.

3.8. Long-term EDAX analysis

Long-term EDAX analysis, i.e., after 3 months, the EDAX spectrum reveals clear and prominent peaks for carbon (C), nitrogen (N), oxygen (O), and phosphorus (P), confirming the continued presence of these core elements in the liposomal matrix. The intensity and position of the peaks suggest that the elemental composition has remained largely consistent, indicating good structural integrity of the liposomes during the observed storage period. carbon (C) constitutes the highest percentage at 61.24%, followed by oxygen (O) at 25.61%, nitrogen (N) at 12.59%, and phosphorus (P) at 0.57%. The dominance of carbon reinforces the organic nature of both the liposomal lipid bilayer and encapsulated compounds, while oxygen and nitrogen levels reflect the typical components of phospholipids and any encapsulated bioactives. The low phosphorus content may suggest either a relatively small proportion of phospholipids in the formulation or partial degradation, although its persistent presence still affirms the structural role of phospholipids. Overall, complete absence of CoQ10 even after 3 months demonstrates that the elemental composition of the liposomal formulation has remained stable over time, particularly in terms of the key structural elements.

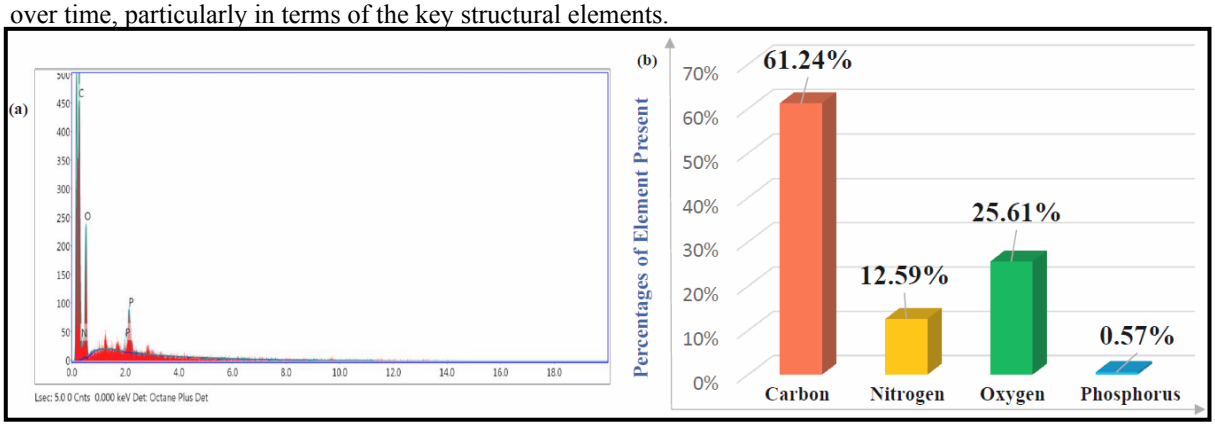

Figure 13: 3 months real time EDAX spectrum of Liposomal CoQ10 showing (a) characteristic peaks for carbon (C), nitrogen (N), oxygen (O), and phosphorus (P), confirming the elemental composition typical of phospholipid-based structures. (b) Quantity of elements present in Liposomal CoQ10

3.9. Stability of CoQ10 Liposomes at Elevated Temperatures

Thermal stability study of liposomal CoQ10 illustrates the stability of liposomal CoQ10 both at RT and elevated temperature of 105°C for 4 hours. The encapsulation efficiency remained consistently high, starting at 81.51% and maintaining to 81.65% throughout the duration of high-temperature exposure, indicating strong stability of CoQ10 within the liposomes. Meanwhile, the assay values for CoQ10 content also remained relatively stable, ranging from 42.56% to 42.00% at RT and 105°C exposure, respectively. These results collectively suggest that the liposomal formulation demonstrates strong structural stability and sustained encapsulation capacity under stressed environmental conditions, supporting its suitability for long-term storage.

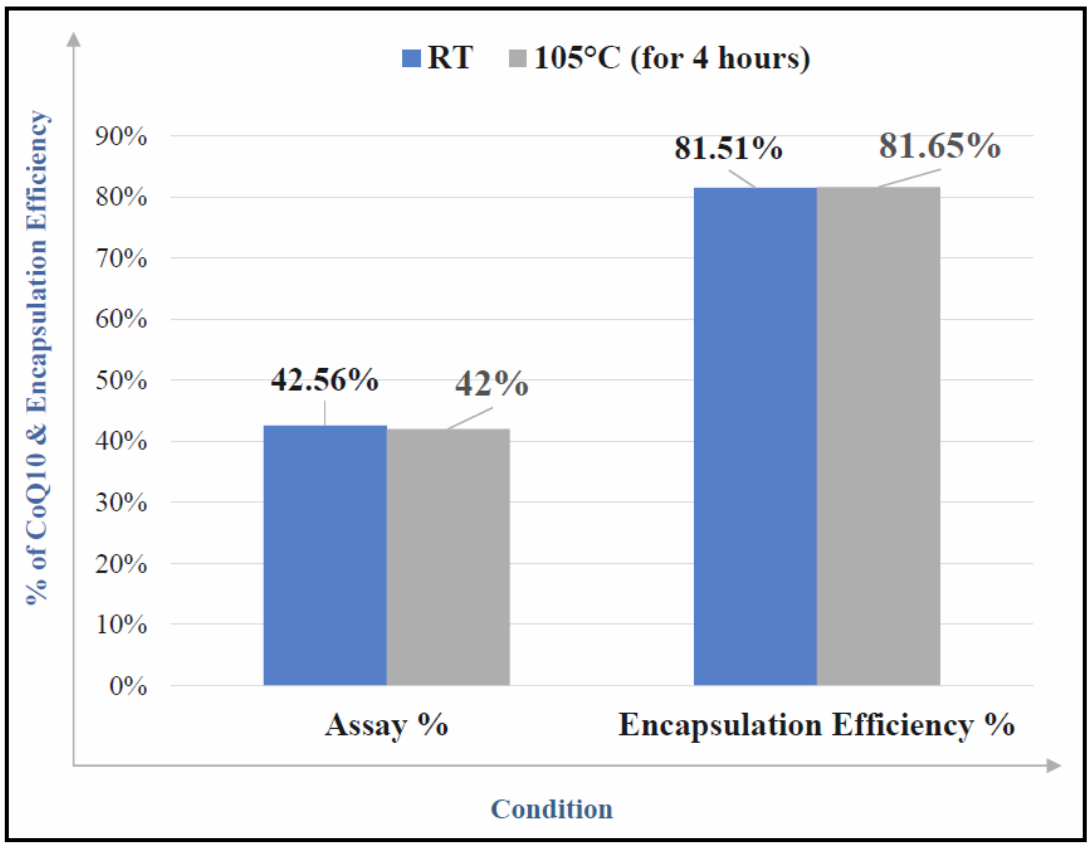

Figure 14: Chart comparing the stability of Liposomal CoQ10 both at RT and at 105°C for 4 hours of exposure

These findings also underscore the superior thermal resilience of liposomal CoQ10, indicating that the phospholipid bilayer provides effective protection against heat-induced degradation. This attribute is particularly important for ensuring product integrity during transportation and storage in high-temperature environments.

3.10. Endothermic Study of Liposomal CoQ10 Using DSC

DSC was conducted to investigate the thermal transitions of pure CoQ10 API, empty liposomes, and liposomal CoQ10. The thermogram of CoQ10 API exhibited sharp melting peaks at 81.72°C and 157.95°C, indicative of its crystalline nature. In contrast, the thermogram of the empty liposomes showed broad transitions at 94.23°C and 288.16°C, corresponding to lipid phase transitions and degradation.

The liposomal CoQ10 formulation displayed three distinct thermal events at 84.81°C, 153.99°C, and 225.67°C. The broadening and shift of these peaks compared to the API and empty liposomes suggest a reduction in crystallinity and strong interaction of CoQ10 with the lipid bilayer. These transitions confirm the successful encapsulation of CoQ10 and the protective effect of the liposomal matrix, which delays thermal degradation.

Table 5: Endothermic Study of Liposomal CoQ10 Using DSC Analysis

Sample	Thermal Events (Peak	Interference/Observations

	Temperatures, °C)	
Coenzyme Q10 API	81.72 / 157.95	Sharp peaks show melting of crystalline CoQ10. Absence of broad transitions confirms pure crystalline form
Liposome	94.23 / 288.16	Peak at ~94°C suggests lipid bilayer phase transition; high-temp peak indicates lipid degradation
Liposomal CoQ10	84.81 / 153.99 / 225.67	Shifted and broadened peaks show reduced crystallinity, interaction with lipid bilayer, and stable encapsulation

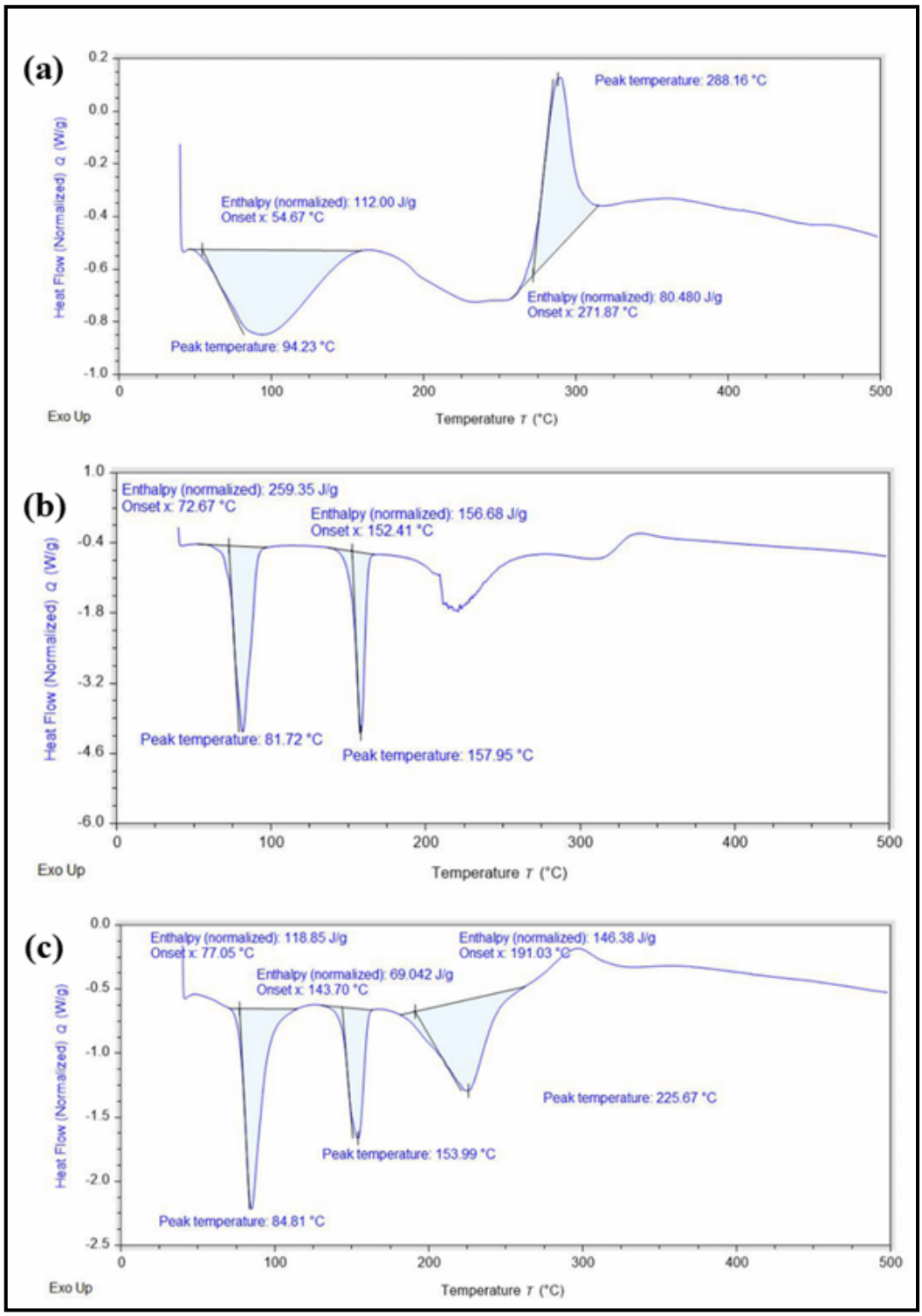

Figure 15: DSC Thermogram of (a) Liposome, (b) CoQ10 API, and (c) Liposomal CoQ10

Overall, the DSC results support the conclusion that WBCIL's liposomal CoQ10 formulation provides enhanced thermal stability, ensuring preservation of the active compound under varied temperature conditions.

IV. Conclusion and Future Prospects

The present study comprehensively evaluated the physicochemical and structural attributes of the liposomal CoQ10 formulation developed by WBCIL. Using advanced analytical and imaging techniques, the formulation was rigorously tested to assess its potential as a viable delivery system for hydrophobic compounds such as CoQ10, which plays an essential role in antioxidant activities, cardiovascular health, and cellular energy production. The results of liposome characterization indicate notable improvements in stability and structural integrity. HPLC analysis showed that the liposomes contained 82.05% Phosphatidylcholine (PC) and 10.82% Phosphatidylethanolamine (PE), contributing to a high total phospholipid content of 93%. FTIR spectroscopy confirmed the structural integrity of the liposomes, revealing characteristic C=O stretching at approximately 1738 cm ^{1}, CH vibrations near 2853 and 2920 cm ^{1}, and broad –OH stretching bands in the range of 3138–3320 cm ^{1}. XPS analysis identified the surface elemental composition as Carbon (81.14%), Oxygen (17.61%), and Phosphorus (1.25%), consistent with the phospholipid-based, biocompatible structure. DLS measurements indicated an average particle size of 133.9 nm with a PDI of 0.294, suggesting a uniform size distribution. The zeta potential was -31.87 mV, indicating strong electrostatic repulsion and good colloidal stability. SEM imaging further confirmed the formation of smooth, spherical vesicles. For the liposomal CoQ10 formulation, DLS analysis showed an average particle size of 150.2 nm with a PDI of 0.3286, reflecting moderate uniformity. The zeta potential was measured at -37.21 mV, suggesting effective electrostatic repulsion and stable colloidal behavior. The encapsulation efficiency of CoQ10 was 81.51%, well above the standard threshold of 70%, indicating efficient entrapment. Accelerated stability testing at 40°C ± 2°C and 75% ± 5% relative humidity demonstrated minimal leakage, with encapsulation efficiencies consistently remaining above 81% over a six-month period. Thermal stability tests showed that the liposomes retained structural integrity and encapsulation efficiency even after exposure to 105°C for 4 hours. Additionally, DSC analysis provided insight into the formulation's thermal behavior, confirming its resilience under heat stress.

Looking forward, the liposomal CoQ10 formulation developed by WBCIL holds significant promise for clinical and commercial development. Future directions could include pharmacokinetic and bioavailability studies in both animal and human models to validate systemic absorption and therapeutic performance. There is potential to explore synergistic formulations by combining liposomal CoQ10 with other antioxidants such as Vitamin E, alpha-lipoic acid, or omega-3 fatty acids to enhance cardioprotective and anti-aging effects. Additionally, incorporation of this formulation into functional foods and beverages may offer innovative delivery platforms for consumers seeking natural and efficient supplementation. Efforts toward large-scale GMP-compliant manufacturing, along with improved shelf-life and packaging solutions, will be essential to commercial success. In summary, WBCIL's liposomal CoQ10 innovation represents a significant advancement in lipid-based drug delivery systems. With its scientific rigor, industrial scalability, and consumer health relevance, this formulation not only addresses the longstanding bioavailability challenges of CoQ10 but also sets a benchmark for future research and development in liposomal encapsulation technologies.

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