https://doi.org/10.15407/microbiolj87.01.072

A.M. KYRYCHENKO[1,2*], O.H. KOVALENKO[1]

[1] Institute of Microbiology and Virology, NAS of Ukraine,
154 Akademika Zabolotnoho Str., Kyiv, 03143, Ukraine
[2] Institute of Biochemistry and Biophysics, Polish Academy of Sciences,
5a Pawińskiego, 02-106 Warsaw, Poland
* Author for correspondence: a.kyrychenko@imv.org.ua

PROSPECTS OF LIPOSOMES APPLICATION IN AGRICULTURE

Liposomes are artificially or spontaneously formed hollow structures whose contents are limited to a single, double, or multiple lipid membrane. Liposomes can be formed by amphiphilic substances encapsulating an aqueous solution of any substance under certain conditions. Liposomes have been very successfully used in the pharmaceutical, cosmetic, and food industries, but there is only limited information on the application of this technology in agriculture. Therefore, the purpose of the review is to summarize the information available since liposome discovery in the 1960s to date on the main properties of liposomes and their production technologies as well as analyze published data on the use of these supramolecular structures in agriculture, mainly as a means of storing, absorbing, and delivering pesticides or antiviral substances to plants.

Keywords: *liposomes, phospholipids, delivery systems, drug delivery, farming industries, plant resistance to viruses.*

History of liposome creation. In the mid-1960s, British hematologist Alec Douglas Bangham and his colleagues, while studying the role of phospholipids in blood clotting and the structure of dispersions formed by the swelling of phospholipids in excess water, discovered lipid vesicles, or liposomes (Bangham & Horne, 1964). Dr. Bangham realized that dried lipids spontaneously rearrange when they come into contact with a sufficient amount of water, demonstrating that this rearrangement is driven by unfavorable interactions between lipids and water, which generate repulsive effects (Trucillo et al., 2020).

In electron micrographs, Bangham observed layered particles that closely resembled cell membranes. This similarity between liposomes and cell membranes provided cell biologists with a valuable tool to study the organization, dynam-

Citation: Kyrychenko A.M., Kovalenko O.H. Prospects of Liposomes Application in Agriculture. *Microbiological journal.* 2025 (1). P. 72—82. https://doi.org/10.15407/microbiolj87.01.072

ics, and properties of the lipid bilayer component in biological membranes (Gregoriadis, 2016). As models of cell membranes, liposomes also allow for the study of specific membrane processes, such as fusion, membrane trafficking, cell adhesion, molecular recognition, and pore formation (Andrade et al., 2021).

Liposomes have also been used to investigate the effects of vitamins, hormones, antibiotics, and other drugs on membranes. This particular property garnered significant attention from researchers, as liposomes proved to be effective as drug carriers. Consequently, liposomes were recognized as promising systems for delivering pharmacologically active agents in the treatment of diseases (Gregoriadis et al., 1971; Gregoriadis & Ryman, 1972a, 1972b). Today, among the wide variety of drug delivery systems, the field of liposomes is one of the fastest-growing scientific topics globally. Currently, the literature on liposomes encompasses around 100,000 articles, with more than 2,000 articles published annually over the past decade. The purpose of this review was to update and summarize the key characteristics of liposomes, the methods for their creation, and the advantages of their applications across various fields.

Liposome composition. Liposomes are synthesized from a variety of components, including cholesterol, glycolipids, sphingolipids, nontoxic surfactants, long-chain fatty acids, and membranous proteins (Magar et al., 2022). The primary chemical components of liposomes are phospholipids, which may come from natural or modified natural sources, as well as semisynthetic or fully synthetic phospholipids with modified head groups. The most commonly used phospholipids for liposome preparation are phosphatidylcholine (lecithin), phosphatidylethanolamine (cephalin), and phosphatidylserine (Trucillo et al., 2020).

When phospholipids are dispersed in water, the molecules naturally aggregate to form a bilayer, minimizing contact between the hydrophobic fatty acid chains and the surrounding hydrophilic aqueous environment. Cholesterol is a crucial lipid that significantly influences the structural properties of liposomes by reducing the permeability of the lipid bilayer. It increases the mechanical rigidity of liposomes, enhancing their stability and preventing undesirable interactions with proteins, which could otherwise impair their performance. Cholesterol also regulates phospholipid packing, membrane fluidity, and surface charge and, as a result, affects the size, morphology, and encapsulation efficiency of liposomes (Lombardo & Kiselev, 2022).

The simplest liposomes are vesicles composed of a double lipid bilayer (Fig. 1A). During the initial spontaneous reorganization of phospholipids, water-soluble drugs can be encapsulated, either within the aqueous core or within the lipid bilayer itself (Trucillo et al., 2020). More advanced liposome formulations, designed for extended circulation, incorporate polyethylene glycol (PEG) or its derivatives. These additions help reduce uptake by macrophages, thus prolonging the presence of liposomes in the bloodstream (Akbarzadeh et al., 2013).

The latest generation of liposomes is characterized by various surface modifications, such as the attachment of protective polymers, diagnostic labels, the introduction of positively charged or stimulus-sensitive lipids, as well as stimulus-sensitive polymers, cell-penetrating peptides, and viral components (Fig. 1B). These liposomes may also contain magnetic particles or gold and silver particles, which are important for magnetic targeting and imaging applications (Trucillo et al., 2020). Additionally, the surface of liposomes can be functionalized with a wide range of ligands, including monoclonal antibodies, peptides, aptamers, and growth factors. This functionalization enhances the specificity of liposome interactions, enabling targeted drug delivery and controlled drug release to specific sites, such as diseased tissues or tumors (Lombardo & Kiselev, 2022).

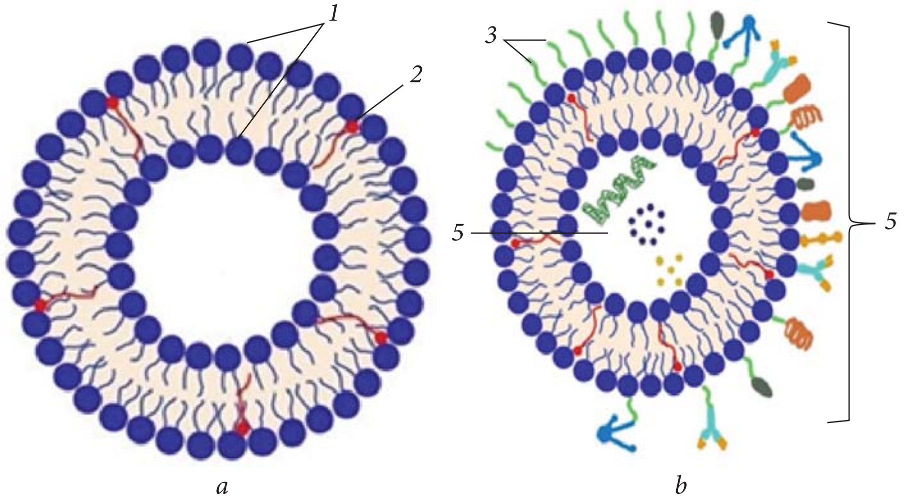

Fig. 1. Schematic representation of liposomal drug delivery systems: (*a*) Conventional liposome, (*b*) Pegylated and ligand-targeted liposome: *1* — phospholipids, *2* — cholesterol, *3* — polyethylene glycol, *4* — ligands (aptamers, charged molecules, proteins, peptides, antibodies, or other receptor-ligand bindings for site-specific targeting), *5* — hydrophilic drug (payload)

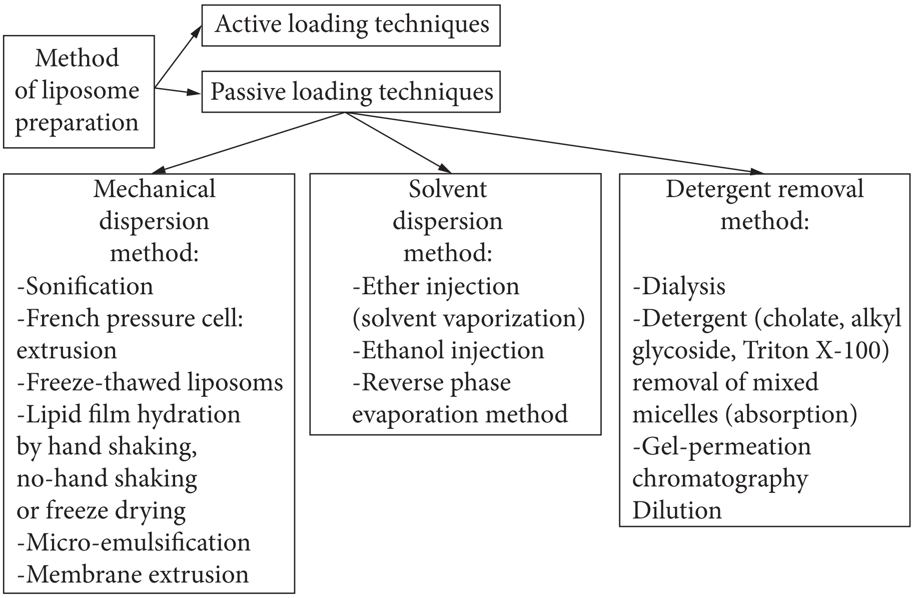

Fig. 2. Methods of liposome preparation and drug loading (according to Akbarzadeh et al., 2013)

Classification of liposomes. Liposomes are classified based on their structural parameters, preparation methods, composition, and application. Their size can range from very small (0.025 μm) to large (2.5 μm) vesicles, and they may have single or multiple bilayer membranes. Morphologically, based on vesicle size and the number of lamellae, liposomes are categorized into small (S), large (L), and giant (G) uni-, oligo-, or multilamellar vesicles (U, O, ML, respectively)

(Danilo, 2000). This classification gives rise to several widely used abbreviations:

- Small unilamellar vesicles (SUV) — 20—100 nm
- Large unilamellar vesicles (LUV) — >100 nm
- Oligolamellar vesicles (OLV) — 100—1000 nm
- Giant oligolamellar vesicles (GOV) — >1000 nm
- Multilamellar vesicles (MLV) — >500 nm.

Methods of liposome preparation. The properties of liposomes vary significantly depending on lipid composition, surface charge, size, and the method of preparation. For drug delivery, there are several established methods for preparing liposomes (Fig. 2). However, all of these methods generally follow four basic stages: (1) drying lipids from organic solvents, (2) dispersing the lipids in an aqueous medium, (3) purifying the resulting liposomes, and (4) analyzing the final product (Magar et al., 2022).

Liposome preparation typically employs either passive or active loading techniques. The passive loading technique encompasses three main approaches: solvent dispersion, mechanical dispersion, and detergent removal (for removing non-encapsulated material) (Magar et al., 2022; Akbarzadeh et al., 2013). Each method has its advantages and disadvantages. Detailed descriptions of the most commonly used liposome preparation methods have been provided in numerous reviews (New, 1990; Reineccius, 1995; Betageri & Kulkarni, 1999; Zeisig & Cämmerer, 2001; Singh et al., 2012; Akbarzadeh et al., 2013; Bozzuto & Molinфari, 2015; Lombardo & Kiselev, 2022; Magar et al., 2022; Gatto et al., 2024; Khan et al., 2024).

Liposome applications in the agricultural industry. Since their discovery in the 1960s, liposomes have been widely used as carriers for drug delivery across multiple industries, including cosmetics (Dymek et al., 2023), medicine (for diagnostics and therapy) (Gatto et al., 2024; Khan et al., 2024), and pharmacology (Akbarzadeh et al., 2013; Lian & Ho, 2001; Bulbake et al., 2017). The food industry has also explored liposomes for delivering nutrients, nutraceuticals, food additives, and antimicrobials (Singh et al., 2012; Pamunuwa & Karunaratne, 2022; Rudzińska et al., 2024). In addition, liposomes have been used successfully in such fields as oncology and gene therapy (Taylor et al., 2005; Himanshu et al., 2016; Olusanya et al., 2018; Gao et al., 2019; Gu et al., 2020; Rommasi & Esfandiari, 2021; Chavda et al., 2022).

Beyond these medical and pharmaceutical applications, liposomes have gained traction in botany and agriculture. They are used as model systems for studying cellular membranes, transmembrane metabolism in plant organelles, drug and reagent delivery systems, and for research on pollen drying tolerance and plant responses to toxins and pesticides. Liposomes have also attracted attention for their potential in encapsulating and delivering various agricultural substances.

An analysis of scientific literature over the past decade reveals a growing interest in using encapsulation technologies in agriculture, particularly for delivering pesticides (Mishra et al., 2020), fertilizers (Vejan et al., 2021), and bioactive compounds (Zabot et al., 2022). Researchers are also exploring new carriers that protect beneficial microorganisms from environmental degradation, which shows promise in advancing agricultural technologies (Jíménez-Arias et al., 2023).

Nano- and microencapsulation of active compounds offers advantages in reducing plant biotic stresses and enhancing growth by extending shelf life and enabling controlled release of biological agents. This innovative approach to managing plant pathogens and alleviating biotic stresses is thoroughly reviewed by Saberi Riseh et al. (2022).

Encapsulating beneficial microorganisms, such as mycorrhizal fungi, plant growth-promoting fungi, and plant growth-promoting rhizobacteria, as well as applying biocontrol bacteria, is considered a promising alternative to chemical fungicides. This approach helps protect crops from phytopathogens while promoting plant growth and reducing harmful pathogens (Jamali et al., 2004; Saberi-Riseh et al., 2004). To preserve the activity of biocontrol bacteria, it is crucial to select an appropriate inoculum formulation and a carrier (Saberi-Riseh et al., 2023a).

Starch-based capsules, used to encapsulate antimicrobial agents or serve as carriers for plant-beneficial microorganisms, are effective tools against phytopathogens (Saberi-Riseh et al., 2023a). While starch has a few limitations as a primary encapsulating matrix, this can be mitigated by combining it with other biopolymers, such as lipids or polysaccharides like plant gum and carboxymethyl cellulose (CMC) (Saberi-Riseh et al., 2023b). CMC, a cellulose derivative, holds great promise for agricultural applications. Nano- and micro-CMC-based formulations for encapsulating and delivering biological control agents (BCAs) and bioactive metabolites are seen as a promising strategy for agriculture (Saberi-Riseh et al., 2022; Cokmus & Elcin, 1995; Fathi et al., 2021; Brondi et al., 2022; Saberi-Riseh et al., 2023a). The use of edible biopolymer-based delivery systems, such as those derived from natural polymers like CMC or starch, provides significant benefits in agriculture. These systems are non-toxic, biocompatible, biodegradable, and environmentally friendly, along with offering cost savings. Targeted delivery of biological and chemical pesticides in such systems improves their efficiency (Saberi-Riseh et al., 2022).

In addition to CMC and starch, research has focused on other biopolymers such as chitosan, alginate, carrageenan, xanthan, and guar gums. Despite the growing use of nanotechnology in agriculture, there has been relatively little research on using liposomes as nanocarriers (Jíménez-Arias et al., 2023). However, recent reductions in lipid costs have opened up opportunities for using liposomes in the agricultural sector. Liposomes can serve as carriers for slow-release formulations of insecticides, biostimulants, fertilizers, and nutrients, and can be used to prime plants and trigger defense responses against pathogens (Taylor et al., 2005; Shao et al., 2022).

Liposomes' ability to carry complex payloads across biological barriers and target specific tissues makes them highly effective for delivering agricultural ingredients to plants. Karny et al. (2018) demonstrated that 100-nanometer liposomes could successfully deliver active ingredients to both seedlings and fully-grown crops. Their study revealed that such liposomes penetrated the plant leaves and moved di-directionally, traveling to both roots and other leaves. Inside the plant, the liposomes released their contents using the plant's natural transport mechanisms, all without causing any toxicity. These findings underscore the potential of liposomal nanotechnology as a promising solution for enhancing plant growth and treating acute nutrient deficiencies in crops (Karny et al., 2018).

Liposomal delivery systems have shown promising results in enhancing the effectiveness of foliar-applied iron (Fe) fertilizers. In particular, liposome-encapsulated Fe (Fe-L) can efficiently deliver iron to plant tissues by overcoming cell membrane barriers. A study by Farshchi et al. (2021) demonstrated that egg-derived phosphatidylcholine (EPC)/Fe-liposomes improved plant health metrics such as fresh and dry weight, total leaf area, chlorophyll levels, ferrous content, and essential oil production compared to traditional $FeSO_4$ fertilizers. This suggests liposomal formulations could be a more efficient alternative to soil fertilization.

Despite the success of liposome technology in agriculture, its potential to boost plant resistance to viral and bacterial diseases remains largely untapped. However, promising results have emerged regarding the use of liposomes to enhance biochemical responses to biotic and abiotic stresses. Several studies have documented the priming effects of botanical extracts encapsulated in nanoscale liposomes, tested under field and lab conditions. This encapsulation improves the uptake and delivery of active plant compounds, boosting plant defense mechanisms (Hegedűs et al., 2022; Kutasy et al., 2022; Decsi et al., 2023). For instance, a plant biostimulant like supercritical carbon dioxide (SC-CO_2) garlic extract encapsulated in liposomes («garlic-lipo») showed better penetration and translocation of its phytochemicals. Genome-wide data from the study indicated that liposome-delivered immunochemicals could trigger plant immune responses, resulting in healthier plants and offering a potential avenue for developing sustainable green plant protection technologies (Kutasy et al., 2022).

Nanoliposomes composed of lipid-based nanomaterials are emerging as promising tools for delivering pesticides. Wang et al. (2022) explored their use in controlling plant virus diseases by delivering antiviral agents through nanoliposome systems. Specifically, they developed a nanoliposome-based biopesticide system encapsulating quercetin, an environmentally friendly antiviral agent, creating a quercetin nano-liposome (H-TQ-NPs). Quercetin (at a concentration of 1 mol/L) effectively inhibited up to 90% of the proliferation of cucumber necrosis virus, turnip crinkle virus, and tobacco mosaic virus in *Nicotiana benthamiana* leaf cells (Wang et al., 2009).

Encapsulating quercetin in nanoliposomes enhanced its delivery into cells, improving its solubility and stability — two crucial factors for controlling phytopathogens. Quercetin's antiviral action is linked to its ability to inhibit the expression of Nbhsp70 proteins, which are upregulated during virus infections or stress and are exploited by viruses for replication. By reducing these proteins, quercetin acts as a potent antiviral agent, even under challenging field conditions (Wang et al., 2009).

The nanoliposome-encapsulated quercetin showed superior efficacy compared to free quercetin. It reduced disease symptoms, such as scorching, leaf shrinkage, and curling during viral infections. The encapsulated version provided a 33.6% and 42% increase in inhibition at the gene and protein levels, respectively, compared to free quercetin. In field experiments, the liposomal formulation demonstrated 38% higher effectiveness against the tobacco mosaic virus (TMV) than traditional methods (Wang et al., 2022). The authors assert that before their exploration of encapsulating quercetin in nanoliposomes and studying its antiviral activity, no studies had focused on using nanocarriers to deliver antiviral agents to plants. However, earlier work by Kovalenko et al. (2019) demonstrated that glycan encapsulated in liposomes formed with rhamnolipids and thiosulfonate could eliminate common bean mosaic virus from infected plant tissues, indicating early advancements in plant viral control through nanocarriers.

Nearly 20 years ago, our laboratory embarked on the development of liposomal glycans as antiviral agents. Our initial findings indicated that biopolymers demonstrated enhanced activity in the presence of surfactants (SAS) (Kovalenko et al., 2006), particularly biosurfactants such as rhamnolipids (Rh-1 and Rh-2) extracted from *Pseudomonas* sp. strain PS-17 (Kovalenko et al., 2008). These rhamnolipids served as the foundation for liposome formation, with cholesterol playing a secondary role as a donor of amino groups, facilitating the binding of carboxyl groups on the rhamnolipids. We successfully developed liposomal formulations of various glycans, including cellular glucan from *Ganoderma adspersum* (Schulzer) Donk, extracellular glucuronoxylomannan from *Tremella mesenterica* Ritz. O., and cellular mannan from *Candida maltosa* (Kovalenko et al., 2017, 2022). These resulting liposomal preparations not only exhibited prophylactic antiviral effects but also positively impacted the symbiotic properties of rhizobial microflora in legumes under field conditions (Kovalenko et al., 2022). In laboratory experiments, liposomes loaded with glucans and mannans showed antiviral activity against tobacco mosaic virus in virus-sensitive plants such as *Datura stramonium* L. and *Nicotiana tabacum* L. (Kovalenko et al., 2017). Additionally, our research has demonstrated for the first time that, in combination with rhamnolipids, thiosulfonates (synthetic analogs of natural biocides) can effectively serve as donors of amine groups for liposome formation. Liposomes formulated with these components and loaded with glycans exhibit highly effective antiviral activity against TMV (Kovalenko et al., 2017, 2022, 2023).

We have investigated the biological activity of these liposomal preparations on seeds of radish, tobacco, tomato, and wheat, as well as on several model plants including tobacco, wheat, and soybeans. The experimental results indicate that loading natural glycans into the liposomes significantly enhances their antiviral activity. The assessments of the phytotoxicity of these liposomal structures at concentrations effective against model viruses confirm their safety and suitability for use on plants. According to our findings, these substances facilitate the penetration of active biopolymers into plant cells with rigid cuticles and cellulose cell walls (Kovalenko et al., 2016).

These complex formulations, composed of glycans, rhamnolipids, and thiosulfonates, also functioned as effective inducers of natural plant resistance and inhibitors of TMV. The effective concentrations of these preparations as resistance inducers in *Nicotiana tabacum* var. Immune 580, which is hypersensitive to TMV, were found to be 10 and 100 μg/mL. At these concentrations, the liposomal preparations also reduce TMV infectivity in *Datura metel* L., demonstrating their role as viral infection inhibitors.

The inducing activity of these complex preparations was sensitive to actinomycin D (10 μg/mL), a known transcription inhibitor (Kovalenko et al., 2023). This observation implies that RNA synthesis plays a crucial role in activating plant virus resistance by the studied preparations. The research results highlight the potential of liposomes composed of rhamnolipids, thiosulfonates, and glycans for targeted delivery of biologically active substances, contributing to increased yields and improved crop productivity in field crops.

Conclusions. The rapidly growing global population and the consequent demand for grain and food products necessitate the search for new ways to enhance agricultural productivity. Challenges such as excessive fertilizer use, environmental pollution, plant diseases, and limited land availability require innovative approaches in crop production technology. One of the promising approaches and solutions is the use of nanotechnologies and nanomaterials in agriculture.

Utilizing biologically active substances of natural origin, which are biodegradable and environmentally friendly, can help reduce environmental pollution. Integrating biological antiviral agents, bioactive stimulants, biopesticides, and nanotechnologies offers a viable solution for combating plant diseases, supplying essential nutrients, and increasing overall crop yields.

While research on liposomal nanotechnologies in agriculture has primarily focused on controlled-release fertilizers and delivery systems for agrochemicals, their potential for crop protection against pests and pathogens remains underexplored.

Given the environmental safety and non-toxicity to humans and animals, liposomal preparations could serve as effective regulators of plant genome activity, phytohormonal status, and immune responses. These bionanomaterials hold promise not only as carriers (smart delivery systems) for agrochemicals and micronutrients but also as inducers and regulators of plant resistance. Research on the effectiveness of these preparations on plant models under field or greenhouse conditions can provide compelling evidence for the feasibility of using these nanopreparations in the agricultural sector. Future research efforts should focus on developing new technologies for creating nanocarriers, such as liposomal preparations using components of biological origin and conducting field trials to assess their biosafety. The application of these formulations represents an environmentally friendly solution for sustainable agricultural production, preserving biodiversity in agricultural lands, and enhancing the viability and productivity of crops, all while avoiding the excessive use of traditional chemical pesticides.

Funding information. This work was supported by project No. PAN.BFB.S.BWZ.407.022.2024, being implemented through the long-term program of support of the Ukrainian research teams at the Polish Academy of Sciences carried out in collaboration with the US National Academy of Sciences and financial support of external partners.

Conflict of interest. The authors declare that they have no conflict of interest.

REFERENCES

Akbarzadeh, A., Rezaei-Sadabady, R., Davaran, S., Joo, S. Wo., Zargham, N., Hanifehpour, Y., Samiei, M., Kouhi, M., & Nejati-Koshki, K. (2013). Liposome: classification, preparation, and applications. *Nanoscale Res Letters, 8*(1), 102.

Andrade, S., Ramalho, M. J., Loureiro, J. A., & Pereira, M. C. (2021). Liposomes as biomembrane models: Biophysical techniques for drug-membrane interaction studies. *Journal of Molecular Liquids*, *334*, 116141.

Bangham, A. D., & Horne, R. W. (1964). Negative Staining of Phospholipids and Their Structural Modification by Surface-Active Agents As Observed in the Electron Microscope. *Journal of Molecular Biology, 8*(5), 660—668.

Betageri, G. V., & Kulkarni S. B. (1999). Preparation of liposomes. In: R. Arshady (Ed.), *Microspheres, microcapsules and liposomes,* 490—521. Citus Books, London, UK.

Bozzuto, G., & Molinari, A. (2015). Liposomes as nanomedical devices. *International Journal of Nanomedicine*, *10*, 975—999.

Brondi, M., Florencio, C., Mattoso, L., Ribeiro, C., & Farinas, C. (2022). Encapsulation of trichoderma harzianum with nanocellulose/carboxymethyl cellulose nanocomposite. *Carbohydrate Polymers. 295*, 119876.

Bulbake, U., Doppalapudi, S., Kommineni, N., & Khan, W. (2017). Liposomal formulations in clinical use: An updated review. *Pharmaceutics*, *9*, 12.

Chavda, V. P., Vihol, D., Mehta, B., Shah, D., Patel, M., Vora, L. K., Pereira-Silva, M., & Paiva-Santos, A. C. (2022). Phytochemical-loaded liposomes for anticancer therapy: an updated review. *Nanomedicine (Lond)*, *17*(8), 547—568.

Cokmus, C., & Elcin, Y. M. (1995). Stability and controlled release properties of carboxymethylcellulose-encapsulated bacillus thuringiensis var. Israelensis. *Journal of Pesticide Science, 45,* 351—355.

Decsi, K., Kutasy, B., Hegedűs, G., Alföldi, Z. P., Kálmán, N., Nagy, Á., & Virágb, E. (2023). Natural immunity stimulation using ELICE16INDURES® plant conditioner in field culture of soybean. *Heliyon, 9*(1), e12907.

Dymek, M., Olechowska, K., Hąc-Wydro, K., & Sikora, E. (2023). Liposomes as Carriers of GHK-Cu Tripeptide for Cosmetic Application. *Pharmaceutics, 15*(10), 2485.

Farshchi, H. K., Azizi. M., Teymouri, M., Nikpoor, A. R., & Jaafari, M. R. (2021). Synthesis and characterization of nanoliposome containing Fe^{2+} element: A superior nano-fertilizer for ferrous iron delivery to sweet basil. *Scientia Horticulturae. 283*, 110110.

Fathi, F., Saberi-Riseh, R., & Khodaygan, P. (2021). Survivability and controlled release of alginate-microencapsulated pseudomonas fluorescens VUPF506 and their effects on biocontrol of rhizoctonia solani on potato. *International Journal of Biological Macromolecules, 183*, 627—634.

Gao, A., Hu, X. L., Saeed, M., Chen, B., Li, Y., & Yu, H. (2019). Overview of recent advances in liposomal nanoparticle-based cancer immunotherapy. *Acta Pharmacologica Sinica*, *40*, 1129—1137.

Gatto, M. S., Johnson, M. P., Najahi-Missaoui, W. (2024). Targeted Liposomal Drug Delivery: Overview of the Current Applications and Challenges. *Life*, *14*, 672.

Gregoriadis, G. (2016). Liposomes in Drug Delivery: How It All Happened. *Pharmaceutics*, *8*(2), 19.

Gregoriadis, G., & Ryman, B. E. (1972a). Fate of protein-containing liposomes injected into rats. An approach to the treatment of storage disease. *European Journal of Biochemistry, 24*, 485—491.

Gregoriadis, G., & Ryman, B. E. (1972b). Liposomal localisation of beta-fructofuranosidase-containing liposomes injected into rats. Some implications in the treatment of genetic disorders. *Biochemical Journal, 129,* 123—133.

Gregoriadis, G., Leathwood, P. D., & Ryman, B. E. (1971). Enzyme entrapment in liposomes. *FEBS Letters, 14*, 95—99.

Gu, Z., Da Silva, C. G., Van der Maaden, K., Ossendorp, F., & Cruz, L. J. (2020). Liposome-Based Drug Delivery Systems in Cancer Immunotherapy. *Pharmaceutics, 12*(11), 1054.

Hegedűs, G., Kutasy, B., Kiniczky, M., Decsi, K., Juhász, A., Nagy, A., Pallos, J. P., & Virág, E. (2022). Liposomal Formulation of Botanical Extracts may Enhance Yield Triggering PR Genes and Phenylpropanoid Pathway in Barley (Hordeum vulgare). *Plants (Basel), 11*(21), 2969.

Himanshu, P., Radha, R., & Vishnu, A. (2016). Liposome and Their Applications in Cancer Therapy. *Brazilian Archives of Biology and Technology, 59*, e16150477.

Jamali, F., Sharifi-Tehrani, A., Okhovvat, M., Zakeri, Z., & Saberi-Riseh, R. (2004). Biological control of chickpea Fusarium wilt by antagonistic bacteria under greenhouse condition. *Communications in agricultural and applied biological sciences, 69*(4), 649—651.

Jíménez-Arias, D., Morales-Sierra, S., Silva, P., Carrêlo, H., Gonçalves, A., Ganança, J. F. T., Nunes, N., Gouveia, C. S. S., Alves, S,, Borges. J. P., & Pinheiro de Carvalho, M. Â. A. (2023). Encapsulation with Natural Polymers to Improve the Properties of Biostimulants in Agriculture. *Plants, 12*(1), 55.

Karny, A., Zinger, A., Kajal, A., Shainsky-Roitman, J., & Schroeder, A. (2018). Therapeutic nanoparticles penetrate leaves and deliver nutrients to agricultural crops. *Scientific Reports. 8*, 7589.

Khan, I. N., Arshad, N., Shaheen, F., Shakoor, R., Hassan, A., & Waqar, M. A. (2024). Recent composition and applications of liposomes in cancer therapy. *International Journal of Polymeric Materials and Polymeric Biomaterials*, 1—13.

Kovalenko, O. G., Kyrychenko, A. M., Shepelevich, V. V., & Barkalova, A. O. (2006). Combined antiphytoviral effect of yeast mannan, some antimetabolites and xenobiotics. *Dopovidi Nacional'noi akademiï nauk Ukrainy, 3*, 153—157. [In Ukrainian].

Kovalenko, O. G., Kirichenko, A. M., Shepelevich, V. V., Karpenko, O. V., Vildanova-Martchyshin, R. I., Scheglova, N. S. (2008). Complex preparations as means of plants recovery and protection against viral infections. *Bulletin of Taras Shevchenko National University of Kyiv. Series: Biology. 51*, 35—37.

Kovalenko, O. G., Vasilev, V. M., Adamchuk-Chala. N. I., Tytova, L. V., & Karpenko, E.V. (2017). Artificial glycan-glycolipid complexes as antiviral means and effectors of microbial formulation on the base of rhizobia. *Dopovidi Nacional'noi akademiï nauk Ukrainy, 1*, 88—96. [In Ukrainian].

Kovalenko, O., Kyrychenko, A., & Kovalenko, O. (2019). Callus cultures of beans infected with virus as a model for testing antiviral compounds. *Journal of Botanical Research, 1*(2), 19–24.

Kovalenko, O. G., Vasilev, V. M., Adamchuk-Chala, N. I., Tytova, L. V., & Karpenko E. V. (2022). Antiviral agents and biological preparations for agriculture based on artificial glycan-glycolipid complexes. *Journal of Ethology & Animal Science, 4*, 000—123.

Kovalenko, O., Kyrychenko, A., Lubenets, V., Pokynbroda, T., Banya, A., Chervetsova, V., & Karpenko, O. (2023). Thiosulphonate-rhamnolipid-glycanic complexes as inducers of virus resistance in hypersensitive plants. *Biologia Plantarum*, *67*, 159—165.

Kutasy, B., Decsi, K., Kiniczky, M., Hegedűs, G., & Virág, E. (2022). Time-course gene expression profiling data of Triticum aestivum treated by supercritical CO_2 garlic extract encapsulated in nanoscale liposomes. *Data Brief, 42*, 108287.

Lasic, Danilo D. (2000). Giant Vesicles: a Historical Introduction. In: P. Luigi Luisi, & P. Walde (Eds.), *Perspectives in Supramolecular Chemistry: Giant Vesicles,* 11—24. John Wiley, New York, USA.

Lian, T., & Ho, R. J. (2001). Trends and developments in liposome drug delivery systems. *Journal of Pharmaceutical Sciences, 90*, 667 — 680.

Lombardo, D., & Kiselev, M. A. (2022). Methods of Liposomes Preparation: Formation and Control Factors of Versatile Nanocarriers for Biomedical and Nanomedicine Application. *Pharmaceutics, 14*(3), 543.

Magar, K. T., George, B., Xiaotong, Li, Chen, Zh., & He, W. (2022). Liposome-based delivery of biological drugs. *Chinese Chemical Letters, 33*(2), 587—596.

Mishra, A., Saini, R. K., & Bajpai, A. K. (2020). Polymer Formulations for Pesticide Release. In S. Thomas, T. K. J. Volova (Eds.), *Controlled Release of Pesticides for Sustainable Agriculture*, 185—206. Springer, Cham, Switzerland.

New, R. R. C. (Ed.), (1990). *Liposomes — a practical approach*. Oxford: IRL at Oxford University Press, UK.

Olusanya, T. O. B., Haj Ahmad, R. R., Ibegbu, D. M., Smith, J. R, & Elkordy, A. A. (2018). Liposomal Drug Delivery Systems and Anticancer Drugs. *Molecules, 23*(4), 907.

Pamunuwa, G. K., & Karunaratne, D. N. (2022). Liposomal Delivery of Plant Bioactives Enhances Potency in Food Systems: A Review. *Journal Of Food Quality, 4*, 1—11.

Reineccius, G. (1995). Liposomes for controlled release in the food industry. In: S. Risch & G. Reineccius (Eds.), *Encapsulation and controlled release of food ingredients,* 113—131. Washington, DC: American Chemical Society.

Rommasi, F., & Esfandiari, N. (2021). Liposomal Nanomedicine: Applications for Drug Delivery in Cancer Therapy. *Nanoscale Research Letters, 16*, 95.

Rudzińska, M., Grygier, A., Knight, G., & Kmiecik, D. (2024). Liposomes as Carriers of Bioactive Compounds in Human Nutrition. *Foods, 13*(12), 1814.

Saberi Riseh, R., Gholizadeh Vazvani, M., Hassanisaadi, M., & Skorik, Y. A. (2023b). Micro-/Nano-Carboxymethyl Cellulose as a Promising Biopolymer with Prospects in the Agriculture Sector: A Review. *Polymers, 15*(2), 440.

Saberi Riseh, R., Hassanisaadi, M., Vatankhah, M., & Kennedy, J. F. (2023a). Encapsulating biocontrol bacteria with starch as a safe and edible biopolymer to alleviate plant diseases: A review. *Carbohydrate Polymers*, *302*, 120384.

Saberi Riseh, R., Hassanisaadi, M., Vatankhah, M., Soroush, F., & Varma, R. S. (2022). Nano/microencapsulation of plant biocontrol agents by chitosan, alginate, and other important biopolymers as a novel strategy for alleviating plant biotic stresses. *International Journal of Biological Macromolecules, 222(Pt A)*, 1589—1604.

Saberi-Riseh, R., Hajieghrari, B., Rouhani, H., & Sharifi-Tehrani, A. (2004). Effects of inoculum density and substrate type on saprophytic survival of Phytophthora drechsleri, the causal agent of gummosis (crown and root rot) on pistachio in Rafsanjan, Iran. *Communications in agricultural and applied biological sciences, 69*(4), 653—656.

Shao, C., Zhao, H., & Wang, P. (2022). Recent development in functional nanomaterials for sustainable and smart agricultural chemical technologies. *Nano Convergence, 9*, 11.

Singh, H., Thompson, A., Liu, W., & Corredig, M. (2012). Liposomes as food ingredients and nutraceutical delivery systems. In N. Garti, D. J. McClements (Eds.), *Encapsulation technologies and delivery systems for food ingredients and nutraceuticals,* 287—318. Woodhead Publishing, Cambrige.

Taylor, T. M., Davidson, P. M., Bruce, B. D., & Weiss, J. (2005). Liposomal nanocapsules in food science and agriculture. *Critical Reviews in Food Science and Nutrition*, *45*(7—8), 587—605.

Trucillo, P., Campardelli, R., & Reverchon, E. (2020). Liposomes: From Bangham to Supercritical Fluids. *Processes, 8*, 1022.

Vejan, P., Khadiran, T., Abdullah, R., & Ahmad, N. (2021). Controlled Release Fertilizer: A Review on Developments, Applications and Potential in Agriculture. *Journal of Controlled Release, 339*, 321—334.

Wang, Y. L., Stork, J., & Nagy, P. D. (2009). A key role for heat shock protein 70 in the localization and insertion of tombusvirus replication proteins to intracellular membranes. *Journal of Virology, 83,* 3276—3287.

Wang. J., Hao, K., Yu, F., Shen, L., Wang, F., Yang, J., & Su, Ch. (2022). Field application of nanoliposomes delivered quercetin by inhibiting specific hsp70 gene expression against plant virus disease. *Journal of Nanobiotechnology, 20*(1), 16.

Zabot, G. L., Schaefer Rodrigues, F., Polano Ody, L., Vinícius Tres, M., Herrera, E., Palacin, H., Córdova-Ramos, J. S., Best, I., & Olivera-Montenegro, L. (2022). Encapsulation of Bioactive Compounds for Food and Agricultural Applications. *Polymers (Basel). 14*(19), 4194.

Zeisig, R., & Cämmerer, B. (2001). Liposomes in the food industry. In P. Vilstrup (Ed.), *Microencapsulation of Food Ingredient*, 101—119. Leatherhead Publishing, London, UK.

Received 03.12.2023

А.М. Кириченко[1,2], *О.*Г. Коваленко[1]

[1] Інститут мікробіології і вірусології ім. Д.К. Заболотного НАН України,
вул. Академіка Заболотного, 154, Київ, 03143, Україна
[2] Інститут біохімії і біофізики, Польська академія наук,
5а Павінського, 02-106 Варшава, Польща

ПЕРСПЕКТИВИ ЗАСТОСУВАННЯ ЛІПОСОМАЛЬНИХ ФОРМ ЗАСОБІВ ЗАХИСТУ РОСЛИН У СІЛЬСЬКОМУ ГОСПОДАРСТВІ

Ліпосоми — це штучно або спонтанно утворені порожнисті структури, що обмежуються одно-, дво- або кількашаровою ліпідною мембраною. До утворення ліпосом здатні амфіфільні речовини, які за певних умов можуть інкапсулювати будь-які речовини з водного розчину. Ліпосоми успішно використовуються у фармацевтичній, косметичній та харчовій промисловості, однак відомості про застосування цієї технології в сільському господарстві досить обмежені. Відтак, метою цього огляду є узагальнити інформацію, доступну з часу відкриття ліпосом у 1960-х роках і дотепер, щодо основних властивостей ліпосом і технологій їх виробництва, а також аналізувати опубліковані дані з використання цих супрамолекулярних структур у сільському господарстві, в основному як засобів збереження, поглинання і доставки пестицидів та антивірусних речовин в рослинах.

Ключові слова: *ліпосоми, фосфоліпіди, системи доставки, доставка ліків, сільське господарство, вірусостійкість рослин.*