Available online on 15.06.2025 at http://jddtonline.info

Journal of Drug Delivery and Therapeutics

Open Access to Pharmaceutical and Medical Research

Open Access Full Text Article

Review Article

Recent Advances in Solid Lipid Nanoparticle Preparation: Methods, Ingredients, and Routes of Administration

Chira Ibrahim Khisho [1]*, Mohanad Alfahad [2]

[1] Department of Pharmaceutics, College of Pharmacy, University of Duhok, Duhok, Iraq

[2] Department of Pharmaceutics, College of Pharmacy, University of Mosul, Ninevah province, Iraq

Article Info:

Article History:

Received 09 March 2025
Reviewed 23 April 2025
Accepted 20 May 2025
Published 15 June 2025

Cite this article as:

Khisho CI, Alfahad M, Recent Advances in Solid Lipid Nanoparticle Preparation: Methods, Ingredients, and Routes of Administration, Journal of Drug Delivery and Therapeutics. 2025; 15(6):175-195 *DOI: http://dx.doi.org/10.22270/jddt.v15i6.7160*

*Address for Correspondence:

Chira Ibrahim Khisho, Department of Pharmaceutics, College of Pharmacy, University of Duhok, Duhok, Iraq

Abstract

Objective: To identify the importance of Solid lipid nanoparticles (SLNs), their most recent methods of preparation and the drugs, lipid(s) and surfactant(s) most recently used for carrier development. **Methods:** Original articles were identified through searches of MEDLINE/PubMed for within the last 5 years (2020-February 2025), with the following search terms; solid lipid nanoparticles. The main aim was to find original articles/ research, this led to another search but excluded evaluation. **Study Selection and exclusion criteria:** Articles that discussed active pharmaceutical "drugs" were selected for this study and exclusion criteria of "NOT review NOT MRNA NOT DNA NOT RNA" to narrow down the articles. **Data Synthesis:** More than 500 articles were identified and further reviewed in the literature and were categorized according to the method in which the SLN were prepared; homogenization and/or high-pressure homogenization, ultrasonication, solvent injection and/or solvent evaporation phase inversion, microemulsion/emulsification, nano spray drying and/or others and combination methods. **Conclusion:** As more specific drug targeting and drug delivery systems become more of an interest in the drug development field, solid lipid nanoparticles will be of continuance importance for a strategic role in nanoparticle formulations.

Keywords: Solid lipid nanoparticles (SLNs), Homogenization, Ultrasonication, Solvent injection

Introduction

Solid lipid nanoparticles (SLNs) most recently have been of high interest in the pharmaceutical industrial fields. The original/initial methods of preparation of SLNs have been patented by professor Gasco since 1991[1]. However, more recently these methods have been tweaked and modified accordingly to the needs of each researcher for the development of drug incorporated into the solid lipids of nano size.

SLNs are typically made up of a solid lipid, a surfactant, an active pharmaceutical ingredient and aqueous medium such as water. Some solid lipids commonly used, although there is no specific guideline, include stearic acid, glycerol monostearate, and cetyl alcohol [2–4]. Surfactant choice and concentration is important not only to decrease the particle size to nano range but also to ensure stability of the lipid particles produced and prevent aggregation. Too high surfactant concentration may also lead to micelle formation and depending on type of surfactant chosen may lead to toxicity [5]. Surfactants of many types haven been successfully used for the preparation of solid lipid nanoparticles; they vary according to their hydrophilicity-lipophilicity balance (HLB). Although majority of surfactants chosen within previous research were selected based upon popularity and trial and error method, the most commonly include; polysorbates, lecithin's and sorbitan esters [5–7]. SLNs should not be confused with nano lipid carriers which in addition to the compositions of SLNs also include a liquid lipid such as oleic acid, glyceryl tricaprylate, isopropyl myristate and glyceryl dioleate [8,9].

In this review, we aim to identify the importance of SLNs and their methods of preparation, the recent advances and development of different drugs within the nanosized solid lipid core, and finally the advancement in recent research in the formulation of SLNs and the methods in which they were prepared.

Advantages of SLNs

Solid lipid nanoparticles, are particles of submicron size below 1000 micrometer. Depending on their route of administration they have found to implicate numerous advantages. The use of SLNs have been widely employed to increase solubility of poorly aqueous soluble drugs.

Majority of drugs are delivered via oral route, as it is the most convenient and less invasive method. Research has shown that drug delivery via solid lipid nanoparticles formulations have led to improve bioavailability, reduce

variation in oral absorption, modulate controlled drug release and have shorter onset of action with longer duration times [10–13] .

Advantages of SLNs formulations via ocular route drug delivery systems have found to improve therapeutic efficiency and increase; ocular permeation, drug pre-corneal retention time, ocular bioavailability and distribution, and drug corneal permeability [14–18]. In addition, SLNs have found to prevent ocular toxicity while maintaining sufficient amount of drug in aqueous humor, vitreous humor and retina [14,19].

Transdermal and topical drug delivery systems have numerous biological barriers which limit the use of therapeutic agents. However, the use of nano lipid carriers such as SLNs have been proven to overcome these biological barriers because their nano size can easily allow permeation through the skin. In addition, to the overall modified and controlled drug release, they promote skin hydration leading to occlusive effects that also aid in drug permeation through the skin. Moreover, the simple components that can be used to formulate SLNs have deemed to be safe on inflamed skin due to their nonirritant and nontoxic nature [20–22]

Nano particles have played an important role in delivery of biological induced drug therapy such as vaccines. They have been widely sought out due to the ability of ease for scaling up manufacturing process. SLNs for parenteral drug delivery have improved bioavailability and like other routes can modify and control drug release. In addition, they have improved stability and have overall reduced clearance and volume of distribution. Due to their nano size researchers have seen enhanced permeability within tumors with increasing retention times leading to a good and promising approach to anticancer targeting drug delivery systems [23–27].

Table 1: Summary of advantages of SLN according to the route of administration

Route of Administration	Advantage(s)	Ref
Oral	Improve bioavailability	[10–13]
	Decrease variation in absorption	
	Modulate controlled drug release	
	Shorter onset of action and longer duration of action	
Ocular	Improve therapeutic efficiency	[14–19]
	Increase ocular permeation	
	Increase drug precorneal retention time	
	Increase ocular bioavailability and distribution	
	Increase drug corneal permeability	
	Prevent/reduce ocular toxicity	
	Maintain sufficient amount of drug in aqueous humor, vitreous humor and retina	
Transdermal	Increase permeation through the skin	[20–22]
	Safe, nonirritant and nontoxic	
	Modified and controlled drug release	
Parenteral	Most widely used for biologic delivery as vaccines	[23–26]
	Improved bioavailability	
	Increase stability	
	Reduce in clearance and volume of distribution	
	Promising approach for anticancer therapy	

Challenges and disadvantages of SLNs

Although the formulation of drugs via solid lipid nanoparticles have been proven to be advantageous, there are still many challenges the researcher may face during the production, storage and administration process. Overall similar disadvantages and challenges the researcher may face are that since SLNs are lipid in nature, there is a limited loading capacity for hydrophilic drugs, drug expulsion during storage and instability of the lipid sized particles may lead to aggregation during storage leading to particle size growth [10,28–30].

Methods

An initial search on MEDLINE/PubMed of solid lipid nano particles within the last five years was conducted in February 2025. This led to 1554 results, in order to narrow the scope of literature available this led to a search of "Solid lipid nanoparticles NOT review NOT MRNA NOT DNA NOT RNA". As a result, 923 articles were available for analysis. The main aim was to find original articles/ research designed to determine the different active ingredients, methods of preparations and lipids and surfactants used. This led to another search but excluded evaluation. Finally, 523 articles were subjected for analysis and were carefully read through to determine researches of interest according to criteria.

Results and Discussion

Accordingly, literature available on PubMed was screened through and summarized according to the method of preparation, active pharmaceutical ingredient, lipid(s) used and surfactant(s) used. These results were summarized and categorized according to the method of which the solid lipid nanoparticles were prepared.

Methods of preparation of SLNs

Recent literature and investigations have sought out multiple innovative methods of preparing solid lipid nanoparticles. These include; high pressure homogenization, solvent injection/solvent evaporation, phase inversion, microemulsion, ultrasonication and others.

High pressure/shear homogenization

The high-pressure homogenization technique is a highly sought out technique due to its simplicity and lack of organic solvent required during processing. This technique requires the preparation of an emulsion consisting of the solid lipid and drug melted to a temperature above the melting point of the lipid followed by addition to the aqueous phase containing the surfactant heated to the same temperature of the lipid solution. This emulsion is then subjected to a high-speed homogenizer with or without pressure as seen by the formation of SLNs of clotrimazole [31]. The presence of pressure is called the high-pressure homogenization method. In the absence of pressure using homogenizer up to 20,000 RPM is known as high shear homogenization method. The homogenizer usually consists of a rotator of high input energy. The emulsion subjected to high speed allows the reduction of particles to a nano size, this emulsion is then allowed to cool for the crystallization of the solid lipid nanoparticles followed by another round of homogenization. Parameters that affect the formation of solid lipid nanoparticles, not only include the formulation design (types and ratios of surfactant and lipid(s) used), but also the rotation speed of the homogenizer, pressure input, time of homogenization and temperature. The main challenge of high-pressure homogenization is the lack of a high energy input homogenizer in small scale laboratories. In addition, the high energy input always leads to increase of temperature of the formulation, thus during the second round of homogenization it is important to keep the system cool as increase in temperature may lead to the coalescence of the particles leading to an increase in size [32].

Table 2: Recently developed Solid lipid nano particles using homogenization and/or high-pressure homogenization method.

Method of preparation	Drug(s)	Lipid(s)	Surfactant (s)	Ref
Homogenization	Gemcitabine And oxaliplatin	Cholesterol Oleic acid	Tween 80 Phosphatidylcholine	[33]
Homogenization	Paroxetine	Glycerol monostearate	Tween 80	[34]
High pressure homogenization	Curcumin	Hydrogenated soybean phospholipids	Poloxamer 188	[35]
High shear homogenization	Combined Rhein and Methotrexate	Glycerol palmitostearate	Poloxamer 188	[36]
High pressure homogenization	Beta carotene	Glycerol stearate Medium chain triglyceride	Tween 80	[37]
High pressure homogenization	Abiraterone acetate	Precirol 5 ATO	Kolliphor 188	[38]
High pressure homogenization	Curcumin	Stearic acid	Poloxamer 188	[39]
High pressure homogenization	Cannabidiol	Compritol 888 ATO	Poloxamer 188	[40]
High pressure homogenization	Beta carotene	Hydrogenated sunflower oil	Soy lecithin	[41]
High pressure homogenization	Irenotecan	Tricaprin	Tween 80	[42]

		Triethanolamine	Span 20	
High shear homogenization	Sulconazole	Glycerol monostearate	Tween 20 Phospholipon 90H	[43]
Homogenization	Fexofenadine	Cetyl palmitate	Tween 20	[44]
Homogenization	Rapamycin	Compritol 888 ATO	Tween 80	[45]
Homogenization	P-methoxycinnamic	Cetyl alcohol	Tween 80	[46]
High pressure homogenization	Apixaban	Glycerol monostearate	Polyethylene glycol 200	[47]
High pressure homogenization	Streptomycin sulphate	Precirol 5 ATO	Tween 80 PEG 600 Phospholipon 90G	[48]
Homogenization	Tetrahydro curcumin	Compritol 888 ATO	Tween 80 Phospholipon 90G	[49]
Homogenization	Revaprazan	Precirol 5 ATO	Tween 80	[50]
Homogenization	Pazopanib	Compritol 888 ATO Precirol ATO 5	Tween 80	[51]
Homogenization	Lawsone	Precirol 5 ATO	Tween 80 Poloxamer 407	[52]
High pressure homogenization	Simvastatin	Precirol ATO 5	Poloxamer 407	[53]
High pressure homogenization	Docetaxel	Compritol 888 ATO	Pluronic F127 Span 80	[54]
High pressure homogenization	Combination of Paclitaxel and Curcumin	Compritol ATO 888 Stearic acid	Tween 80	[55]
Homogenization	Valsartan	Precirol 5 ATO	Gelucire 50/13 Pluronic 188	[56]
High pressure homogenization	Monoterpenes (alpha-pinene, citral geraniol or limonene)	Imwitor 900K	Poloxamer 188	[57]
Homogenization	Vancomycin	Lineolic acid	Tween 80	[58]
High pressure homogenization	S-adenosyl-Lmethionine	Tristearin	Tween 80	[59]
High pressure homogenization	Zataria multiflora	Stearic acid	Span 60 Tween 80	[60]
Homogenization	Combination of Donepezil and rhodamine B	Dynasan 116	Tween 80	[61]
Homogenization	Ferulic acid	Compritol ATO 888	Tween 80	[62]
Homogenization	Simvastatin	Compritol ATO 888 Precirol 5 ATO Geleol	Poloxamer 407 Tween 80	[63]
Homogenization	Fucoxanthin	Coconut oil Glyceryl monostearate	Tween 80 Soy lecithin	[64]

Homogenization	Bedaquiline	Lecithin	Tween 80	[65]
Homogenization	Myricetin	Gelucire Compritol 888 ATO	Poloxamer 407	[66]
High pressure homogenization	Curcumin	Compritol 888 ATO Glyceryl monostearate	Tween 80 Phospholipon 90G	[67]
Homogenization	Melatonin	Compritol ATO 888	Poly vinyl alcohol	[68]

Ultrasonication

Ultrasonication method involves the use of a probe or bath sonicator which allows the breakdown of the formed particles into smaller nano sizes. This method highly depends upon the time of sonication and temperature applied. In addition, sonication of samples for long periods of time may lead to overheating, thus intermittent sonication has been employed to overcome this problem [69]. Particles developed using ultrasonication method may not be as small as high-pressure homogenization however, combination use with other methods have found successful preparations of solid lipid nanoparticles as can be seen in table 3.

Table 3: Recently developed Solid lipid nano particles using ultrasonication technique.

Method	Drug	Lipid(s)	Surfactant(s)	Ref
Sonication	Lacitin 3147	Softisan 601	Kolliphor RH40 Transcutol P DMSO	[70]
Sonication	Nisin Z peptide	Softisan 601	Kolliphor RH40 Transcutol P DMSO	[71]
Sonication	Vitamin A	Stearic acid	Tween 80	[72]
Sonication	Ibuprofen or hydrocortisone	Witepsol	Sodium cholate Cremophor A25	[73]
Sonication	Curcumin	Cetyl palmitate	Tween 60	[74]
Sonication	Triamcinolone acetonide	Stearic acid	Soy PC Tween 80	[75]
Sonication	Pterostilbene	Compritol 888 ATO	Poloxamer 188 and poloxamer 407	[76]
Sonication	Rifampicin	Cetyl palmitate	Tween 80	[77]
Sonication	Vitamin A	Beeswax	Tween 80 Span 80	[78]
Sonication	Gliclazide	Compritol 888 ATO	Poloxamer 188	[79]
Sonication	Clozapine	Glyceryl behenate	Tween 80 Poloxamer 188	[80]
Sonication	Mitoxantrone	Cetyl palmitate	Tween 80	[81]
Sonication	Ascorbyl palmitate	Glyceryl monostearate	Pluronic F-68	[82]
Sonication	Mitoxantrone	Compritol ATO 888 Octadecyl amine	Tween 80	[83]
Sonication	Sulforaphene	Glyceryl monostearate	Sodium caseinate	[84]
Sonication	Simvastatin	Compritol 888 ATO	Gelucire 40/14	[85]

			Poloxamer 407	
Sonication	Dimethyl fumarate	Glyceryl monostearate	Poloxamer 188 Hydrogenated soy phosphatidylcholine	[86]
Sonication	Combination of Paclitaxel and photothermal agent IR-780	Tricaprin Cetyl palmitate	Pluronic F-68	[87]
Sonication	Cyclosporine A	Softisan 649	Tween 80	[88]
Sonication	Griseofulvin	Stearic acid	Chitosan	[89]

Abbreviation: DMSO, Dimethyl sulfoxide

Solvent injection/Solvent evaporation

The lack of a sophisticated piece of equipment such as high-pressure homogenizer makes the solvent injection/evaporation technique more popular within small scale laboratories. This method involves the addition of the lipid phase solution to the aqueous phase solution heated to the same temperatures by the use of a syringe. The aqueous phase should be maintained at a controlled temperature with constant stirring or agitation usually accomplished by the use of magnetic stirrer. However, the use of an organic solvent usually; ethanol or methanol is required. Suitable methods or time is required until complete evaporation of the solvent [90]. One study done for the development of adapalene SLNs, injected the lipid solution at a constant flow rate [91] which is similar to the methods employed for the development of antifungal miconazole SLNs [92]. In contrast, in another study mometasone lipid phase was rapidly injected into the aqueous phase [93] . These different addition techniques and different stirring speeds and times allows modifications in preparation of the SLNs. Despite the initial stage of solvent injection, the use of sonication is usually used in combination to ensure stable nano sized particle production.

Table 4: Recently developed solid lipid nanoparticles using solvent injection and/or solvent evaporation technique.

Method of preparation	Drug(s)	Lipid(s)	Surfactant (s)	Ref
Solvent-evaporation	Cryptolepine	Stearic acid	Poloxamer 188	[94]
Solvent evaporation	Tacrolimus	Stearic acid	Tween 80 Sorbitan monooleate	[95]
Solvent evaporation	Microalgae omega 3	Softisan 649	Tween 80 Soy lecithin	[96]
Solvent injection	Prednisolone acetate	Compritol 888 ATO	Tween 80 Pluronic	[97]
Solvent evaporation	Cryptolepine	Stearic acid	Poloxamer 188	[98]
Solvent injection	Rhynchophylline	Glycerol monostearate	Tween 80 Solutol HS 15	[99]
Solvent evaporation	Naloxone	Glycerol monostearate	Pluronic 127 Tween 80	[100]
Solvent evaporation	Doxorubicin	Stearic acid Soy lecithin	Poloxamer 188	[101]
Solvent evaporation	Rapamycin	Compritol ATO 888	Tween 80	[102]
Solvent injection	Naringenin	Glyceryl tristearate Lecithin	Tween 80 Poloxamer 407	[103]

Phase inversion

The phase-inversion temperature method is a low-energy approach for determining the solubility of polyethoxylated nonionic surfactants when temperatures vary. At high temperatures, the surfactant transitions from hydrophilic to hydrophobic, resulting in negative curvatures and water-swollen reverse micelles. At a certain temperature (the PIT temperature), the surfactant has an affinity for both the oil and water phases, resulting in no spontaneous curvature and exceptionally low interfacial tension values. When the temperature falls below PIT, hydrated nonionic surfactants have high water solubility and produce fine droplets. The preparation of SLNs using phase inversion temperature technique is very limited within the literature with very few having successful outcomes [104].

Table 5: Recently developed solid lipid nanoparticles using phase inversion method

Method of preparation	Drug(s)	Lipid(s)	Surfactant (s)	Ref
Phase inversion temperature	Loratadine	Beeswax	Tween 80	[105]
Phase inversion Temperature	Querectin	Tripalmitin and/or Glycerol monostearate and/or Stearic acid	CRH 40 Kolliphor EL Tween 60 Tween 80	[104]
Phase inversion temperature/ sonication	benzo[k,l]xanthene lignans	Precirol ATO 5	Tween 80	[106]

Microemulsion

The microemulsion or emulsification method was first introduced by Gasco in 1993 [107] Recent literature have used similar methods with various modifications. The production of oil in water emulsion is produced by melting lipid phase separately and heating aqueous phase with surfactant separately. The heated aqueous phase is then added to the lipid phase with continuous stirring usually on a magnetic stirrer to produce an o/w emulsion. This emulsion is then added to cold water to produce a dispersion of SLN. The ratio of emulsion to cold water varies in literature and may range from a 1:10 ratio to 1:50 ratio, emulsion: water [108,109]. However, due to the low input of energy particles produced may not be as small as those compared to high pressure homogenization and other techniques.

Table 6: Recently developed solid lipid nanoparticles using Microemulsion/emulsification methods

Method of preparation	Drug(s)	Lipid(s)	Surfactant (s)	Ref
Solvent emulsion	Querectin	Glyceryl stearate Cholesterol lecithin	Tween 80	[110]
Microemulsion	Orobol	Capmul	Transcutol Labrasol	[111]
o/w Emulsion	Purpurin-18-N-propylimide methyl ester	Palmitic acid or Glycerol monostearate	Tween 20 or poloxamer 188	[112]
Emulsification	Dopamine	Glycerol tripalmitin	Tween 80	[113]
Microemulsion	Hydroquinone	Stearic acid	Tween 20	[114]
Microemulsion	Trans-ferulic acid	Compritol 888 ATO	Kolliphor EL Transcutol P	[115]
Double emulsion	Albendazole	Beeswax	Poloxamer 407	[116]
Solvent emulsification	Flurbiprofen	Stearic acid	Tween 80	[117]
Emulsification	Dopamine	Gelucire 50/13	Tween 85	[118]

Microemulsion	Isoniazid Pyrazinamide Rifampicin	Stearic acid Compritol 888 ATO	Poloxamer 188 Sodium taurocholate	[119]
Microemulsion	Lacticin 3147	Softisan 601	Kolliphor HS15 Kolliphor RH40	[120]
Microemulsion	Leflunomide	Compritol 888 ATO	Tween 80 Phospholipon 90G	[121]
Microemulsion	Chondroitin sulfate	Stearic acid Octadecylamine	Poloxamer 188	[122]
Emulsification	Resveratrol	Stearic acid Lecithin	Myrj 52	[123]
Emulsification	Nintedanib	Glyceryl monostearate Stearic acid Palmitic acid	Tween 80 Poloxamer 188	[124]
Microemulsion	Topotecan	Tricaprin	Tween 80 Span 20	[125]
Microemulsion	Amorolfine HCL	Stearic acid Monostearin	Sodium taurocholate Sodium tauroglycholate	[126]
Double emulsification	Tanespimycin	Precirol ATO 5 Glycerol Sorbitan monostearate	B-cyclodextrin Tween 80	[127]
Double emulsification	Combination streptomycin and hydroxychloroquine	Stearic acid Lecithin	Poloxamer	[128]
Double emulsification	Hydroxyzine HCL	Compritol 888 ATO	Soy lecithin Tween 80	[129]
Microemulsion	Chlorophyll	Trilaurin	Epikuron 200 Cremophor RH	[130]
Microemulsion	Econazole	Tripalmitic glyceride Glycerol	Tween 80	[131]
Emulsification	Resveratrol	Stearic acid Lecithin	Myrj 52	[132]
Double emulsion	Pralidoxime	Dynasan 114 Lipoid S75	Tween 80	[133]
Emulsification	Palmitoylethanolamide	Stearic acid Cholesteryl stearate	Span 85 Pluronic F68	[134]
Microemulsion	Docetaxel palmitate	Palmitic acid OR Stearic acid OR GMS OR Cetyl palmitate	Tween 80	[135]
Emulsification	Ambrisentan	Glyceryl monostearate	Tween 80	[136]

Abbreviation: HCL, hydrochloride

Nano Spray Drying/ Others

Spray drying technique has been explored as a method to increase the stability of nanoparticles due to the aggregation of particles during storage in a dispersed solution, especially drugs that are highly susceptible to high temperatures and light. This method has been suggested to be a one step process, leading to reduction of costs during the processing steps. Major limitations to this technique include the tendency of the spray dried lipids to stick to surfaces leading to difficulties in recovering of the particles, coalescence and solid-state transition of irregular lipid crystals produced by spray dry method. Although, reduction of particles to nano size may be achievable by spray drying method it is important to also consider the reconstitution properties of the dried nanoparticles. They should be able to be reconstituted with selected aqueous medium to the same nano sized particles without rapid agglomeration. Therefore, there are many factors that need to be considered before the optimum formulation is selected as final product. Factors as drying time, drying temperature, type and amount of lipid used and type and amount of surfactant used [137–139].

Table 7: Preparation of Solid lipid nanoparticles using methods that are not as frequent

Method	Drug	Lipid(s)	Surfactant(s)	Ref
Nano template engineering using micro syringe filter	Melatonin	Palmityl alcohol	Span 40 Tween 80 Myrj 52	[140]
Hot melt extrusion/ sonication	Tilmicosin	Carnauba wax	PVA or PVP or Poloxamer 188	[141]
Hot melt extrusion	Docetaxel	Glycerol monostearate	PEG 2000	[142]
Effervescent dispersion	Felodipine	Glyceryl behenate	Tween 80 Poloxamer 188	[143]
Supercritical	Hesperidin	Stearic acid	Tween 80	[144]
Microfluidic preparation	Trypsin or testosterone	Cetyl palmitate	Tween 80 Pluronic 68 Soy lecithin	[145]
Solvent diffusion	Rifampicin	Glyceryl monostearate		[146]
Solvent diffusion	B-carotene	Palmitic acid	Poloxamer 407	[147]
Thin film sonication	Curcumin	HSPC	PVP K15	[148]
Nano spray drying	5-Fluorouracil	Palmitic acid	PVA	[149]

Abbreviations: PVA, polyvinyl alcohol; PVP, poly vinyl pyrrolidine

Combination methods

To overcome coalesces and increase the stability of nano emulsions, an innovative method by Glaubitt, introduced combination of a standard method of preparation of nanoparticles and spray drying. By combining ultrasound-assisted or high shear homogenization with spray drying it was assumed to increase the stability of the otherwise unstable long-term emulsions while keeping the nano sized particles (preventing irregular crystals) [137] .

Table 8 gives an indication of recent development of SLNs using combination of techniques. This proves that the use of more than one method is beneficial to overcome problems during the formulation of SLNs, whether the issue being stability, coalesces, preventing degradation and also to achieve desired nano particle size that may not have been achieved if prepared using a single method.

Table 8: Recently developed solid lipid nanoparticles using a variety/ combination of methods

Method	Drug	Lipid(s)	Surfactant(s)	Ref
Combination of double emulsion and melt dispersion	Ferrous sulfate	Monolaurin Stearic acid	Tween 80	[150]
Single emulsification and Double emulsification	Sodium aescinate	Glycerol monostearate Egg yolk lecithin	Poloxamer 188	[151]
Combination hot homogenization and sonication	Querctine	Cetyl palmitate	Tween 80	[152]
Solvent evaporation/ emulsification	Mangiferin	Cholesterol egg phosphatidylcholine	Poloxamer 407	[153]
Solvent injection and homogenizer and sonication	Nystatin or fluconazole	Glycerol monostearate	Tween 80 Soy lecithin	[154]
Solvent evaporation/ sonication	Bimatoprost	Glycerol monostearate	Poloxamer 407	[155]
Emulsification/ evaporation	Morin hydrate	Glycerol monostearate	Tween 80 Soy lecithin	[156]
Emulsification/ sonication	Tolfenamic acid	Stearic acid	PVA	[157]
Emulsification/ homogenization and then Spray drying	Levofloxacin	Stearic acid	Tween 80 PEG 4000	[158]
Sonication/ homogenization	Paclitaxel	Stearic acid	Kolliphor 188	[159]
Emulsification/ sonication	Curcumin	Softisan 100	Emulmetik 900 Solutol HS 15	[160]
Emulsification/ sonication	Curcumin	Medium and long chain diacylglycerol or glycerol tripalmitate	Tween 20 or Quillaja saponin	[161]
Emulsification/ sonication	Beta hydroxybutyric acid, carmustine and temozolomide	Cetyl palmitate	Tween 80	[162]
Homogenization/ sonication	RVG-29 or Quercetin	Cetyl palmitate	Tween 80	[163]
Solvent emulsification/ sonication	Morin	Compritol 888 ATO	Tween 80 Phospholipon 80H	[164]
Microemulsion/ sonication	Mannose-6-Phosphate-Human serum albumin-matrine	Glycerol monostearate	Poloxamer 188	[165]
Emulsification/ sonication	Tetrahydrocurcumin	Glycerol monostearate	Tween 80 Soy lecithin	[166]
Solvent injection/ sonication	Paclitaxel or Sorafenib	Cetyl palmitate	Pluronic F68 Poly ethylene glycol	[167]
Homogenization/ sonication	Hesperidin	Precirol 5 ATO	Poloxamer 188 Span 80	[168]
Emulsification/ solvent evaporation	Gellan gum, Alginate and Nisin	Stearic acid	Poly vinyl alcohol	[169]
Homogenization/ sonication	Loteprednol	Precirol ATO 5	Tween 80	[170]

Emulsification/ solvent evaporation	Estradiol	Compritol 888 ATO Precirol ATO 5	Pluronic F127 Tween 80	[171]
Hot melt extrusion/ homogenization	Alprazolam	Compritol 888 ATO	Tween 20	[172]
Emulsification/ high pressure homogenization	Vitamin D	Precirol 5 ATO	Tween 80	[173]
Emulsification/ sonication	Budesonide	Compritol 888 ATO	Sodium cellulose sulphate	[174]
Emulsification/ solvent evaporation	Phytol	1,3-distearyl-2-oleyl glycerol	Poly vinyl alcohol	[175]
Double emulsion/ solvent evaporation	Gemcitabine	Glycerol monostearate	Soy lecithin Pluronic F127	[176]
Homogenization/ emulsification	Retinol and Pentapeptide-18	Glyceryl monostearate, hexadecyltrimethylam monium, L-phosphatidylcholine	Tween 80 Sodium cholate	[177]
Homogenization/ sonication	Cannibidiol	Glyceryl mono stearate	Tween 80	[178]
Homogenization/ sonication	8-Methoxypsoralen	Compritol 888 ATO	Poloxamer 188 Transcutol P	[179]
High pressure homogenization/ sonication	Verapamil	Stearic acid	Poloxamer 188	[180]
Homogenization/ sonication	Amiodarone	Witepsol W 35 Glyceryl monostearate	Poloxamer Sodium lauryl sulfate Soy lecithin	[181]
Double emulsification/ sonication	Vildagliptin	Stearic acid	Tween 80 Span 80	[182]
Homogenization/ sonication	Atorvastatin calcium	Compritol 888 ATO Lipoid S100	Gelucire 50/13	[183]
Homogenization/ sonication	Metformin	Glyceryl monostearate	Span 60 Tween 80	[184]
Emulsification/ evaporation/ sonication	Sunitinib	Glyceryl monostearate	Tween 80 Span 80	[185]
Emulsification/sonication	Gefitinib	Stearic acid	Pluronic F-68	[186]
Homogenization/ sonication	Kojic acid	Glyceryl monostearate Cholesterol	Span 60 Tween 20	[187]
Solvent injection/ sonication	Atorvastatin	Glyceryl monostearate	Tween 40 Span 80	[188]
Emulsification/ evaporation	Valsartan	Glyceryl monostearate Egg lecithin	Poloxamer 407	[189]
Emulsification/ sonication	Mirabegron	Glyceryl monostearate	Tween 80	[190]
Homogenization/ sonication	Caffeic acid	Compritol 888 ATO	Tween 80 Pluronic F127	[191]

Emulsification/ solvent evaporation	Combination Amphotericin B and paromomycin	Glyceryl monostearate	Tween 80 Soy lecithin	[192]
Double emulsification/ sonication	Insulin	phosphatidylcholine	Poloxamer 188	[193]
Sonication/ film dispersion	Combination curcumin and paclitaxel	Hydrogenated soybean phospholipids	Polyvinyl pyrrolidone k15	[194]
Microemulsion/ homogenization	Bedaquiline	Capmul MCM C10	Phospholipon 90G Poloxamer 188	[195]
Homogenization/ sonication	Acyclovir	Compritol ATO 888	Tween 80	[196]
Solvent evaporation/ homogenization	Metronidazole	Precirol ATO 5	Tween 80	[197]
Homogenization/ sonication	Foeniculum vulgare	Stearic acid	Phosphatidylcholine Tween 80	[198]
Emulsification/ homogenization	Naringenin	Glyceryl monooleate	Tocopheryl polyethylene glycol succinate	[199]
Homogenization/ sonication	Rifampicin	Glycerol tripalmitate	Tween 80	[200]
Emulsification/ sonication	Alpha-asarone	Precirol 5 ATO Palmitic acid	Gelucire 53/13 Tween 80	[201]
Emulsification/ solvent evaporation	Perphenazine	Glyceryl monostearate Lecithin	Tween 80	[202]
Homogenization/ sonication	Combination of Docetaxel and erlotinib	Precirol 5 ATO	Tween 20	[203]
Solvent injection/ homogenization	Oxiconazole nitrate	Tyloxapol Stearic acid	Tween 80 Poloxamer 407	
Homogenization/ sonication	Paclitaxel	Precirol 5 ATO Stearic acid	Tween 20 Poloxamer 407 Soy lecithin	[204]
Solvent injection/ sonication	Acyclovir	Stearic acid	Tween 80	[205]
Emulsification/ solvent evaporation	Curcumin	Stearic acid	Myrj 52 Soy lecithin	[206]
High Pressure homogenization/ sonication	Capsaicin	Compritol ATO 888 OR Glyceryl monostearate AND Cetyl alcohol OR Stearyl alcohol	Span 80 Tween 80	[207]
Emulsification/ sonication	Brigatinib	Stearic acid	Soy lecithin	[208]
Homogenization/ sonication	Gabapentin	Cholesterol OR Stearic acid	Tween 80 OR Pluronic F-68	[209]
Homogenization/ solvent evaporation	Beta sitosterol	Compritol ATO 888	Phospholipon 90G Tween 80	[210]
Emulsification/ solvent evaporation	Letrozole	Tripalmitin glyceride Octadecylamine	Tween 80	[211]

Emulsification/ sonication	Insulin	Compritol ATO 888	Soy lecithin Poloxamer 407	[212]
High pressure homogenization	Bromelain	Stearic acid Tristearin	Tween 80 Span 80	[213]
Emulsification/ solvent evaporation	Curcumin	Stearic acid	Myrj 52 Soy lecithin	[214]
Homogenization/ sonication	Lavender oil	Cholesterol Lecithin	Tween 80	[215]
Emulsification/ solvent evaporation	Delafloxacin	Stearic acid	Pluronic F-127	[216]
Emulsification/ solvent evaporation	Cilnidipine	Compritol ATO 888	Poloxamer 188	[217]
Homogenization/ sonication	Penicillin	Compritol ATO 888	Lutrol F68	[218]
Homogenization/ sonication	Paclitaxel	Precirol 5 ATO Stearic acid Lecithin	Tween 20 Poloxamer 407	[219]
Emulsification/ homogenization	Cannabidiol	Compritol ATO 888 Witepsol E85	Tween 80 Poloxamer 188	[220]
Emulsification/ sonication	Combination of curcumin and Lawsone	Cetyl palmitate	Polyethylene glycol 400	[221]
Emulsification/ sonication	Abemaciclib	Precirol 5 ATO	Brij 58	[222]
Emulsification/ sonication	Acalabrutinib	Compritol ATO 888 Stearyl palmitate	Tween 80 Poloxamer 188	[223]
Homogenization/ sonication	Vancomycin	Compritol 888 ATO	Lurol F68	[224]

Abbreviation: PVA, poly vinyl alcohol

Conclusion

Development of drugs incorporated with SLNs have been widely explored within recent years. They have been used for specific drug delivery/targeting. Many methods with modifications of each method have been explored depending on specific needs and requirements of the final SLN. The nano size of SLN have found to have advantages within literature but further exploration is required, in addition although SLN have been described within literature very few have been patented and available within the market. Although there have been some formulations described, investigations within preclinical and clinical trials make the use of drug incorporated within SLN a promising future in drug delivery.

Conflict of interest: The authors confirm there is no conflict of interest.

Author Contributions: All authors have equal contribution in the preparation of manuscript and compilation.

Source of Support: Nil

Funding: The authors declared that this study has received no financial support.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting in this paper are available in the cited references.

Ethical approval: Not applicable.

References

[1] Method for producing solid lipid microspheres having a narrow size distribution 1991.

[2] Argimón M, Romero M, Miranda P, Mombrú ÁW, Miraballes I, Zimet P, et al. Development and characterization of Vitamin A-loaded solid lipid nanoparticles for topical application. J Braz Chem Soc 2017;28:1177–84. https://doi.org/10.21577/0103-5053.20160276

[3] Ekambaram P, Abdul Hasan Sathali A. Formulation and Evaluation of Solid Lipid Nanoparticles of Ramipril. Journal of Young Pharmacists 2011;3:216–20. https://doi.org/10.4103/0975-1483.83765 .

[4] Tiyaboonchai W, Tungpradit W, Plianbangchang P. Formulation and characterization of curcuminoids loaded solid lipid nanoparticles. Int J Pharm 2007;337:299–306. https://doi.org/10.1016/J.IJPHARM.2006.12.043 .

[5] Helgason T, Awad TS, Kristbergsson K, McClements DJ, Weiss J. Effect of surfactant surface coverage on formation of solid lipid nanoparticles (SLN). J Colloid Interface Sci 2009;334:75–81. https://doi.org/10.1016/J.JCIS.2009.03.012 .

[6] Yasir M, Vir Singh Sara U, Som I, Gaur P, Singh M, Ameeduzzafar . Nose to Brain Drug Delivery: A Novel Approach Through Solid Lipid Nanoparticles. Current Nanomedicine 2016;6:105–32. https://doi.org/10.2174/2468187306666160603120318 .

[7] Dal Pizzol C, Filippin-Monteiro FB, Restrepo JAS, Pittella F, Silva AH, de Souza PA, et al. Influence of Surfactant and Lipid Type on the Physicochemical Properties and Biocompatibility of Solid Lipid Nanoparticles. Int J Environ Res Public Health 2014;11:8581. https://doi.org/10.3390/IJERPH110808581 .

[8] García-Pinel B, Porras-Alcalá C, Ortega-Rodríguez A, Sarabia F, Prados J, Melguizo C, et al. Lipid-Based Nanoparticles: Application and Recent Advances in Cancer Treatment n.d. https://doi.org/10.3390/nano9040638 .

[9] Park SJ, Garcia C V., Shin GH, Kim JT. Development of nanostructured lipid carriers for the encapsulation and controlled release of vitamin D3. Food Chem 2017;225:213–9. https://doi.org/10.1016/j.foodchem.2017.01.015 .

[10] Zhuang CY, Li N, Wang M, Zhang XN, Pan WS, Peng JJ, et al. Preparation and characterization of vinpocetine loaded nanostructured lipid carriers (NLC) for improved oral bioavailability. Int J Pharm 2010;394:179–85. https://doi.org/10.1016/J.IJPHARM.2010.05.005 .

[11] Zhang Y, Li Z, Zhang K, Yang G, Wang Z, Zhao J, et al. Ethyl oleate-containing nanostructured lipid carriers improve oral bioavailability of trans-ferulic acid ascompared with conventional solid lipid nanoparticles. Int J Pharm 2016;511:57–64. https://doi.org/10.1016/J.IJPHARM.2016.06.131 .

[12] Garg A, Bhalala K, Tomar DS, Wahajuddin. In-situ single pass intestinal permeability and pharmacokinetic study of developed Lumefantrine loaded solid lipid nanoparticles. Int J Pharm 2017;516:120–30. https://doi.org/10.1016/J.IJPHARM.2016.10.064 .

[13] Müller RH, Runge S, Ravelli V, Mehnert W, Thünemann AF, Souto EB. Oral bioavailability of cyclosporine: solid lipid nanoparticles (SLN) versus drug nanocrystals. Int J Pharm 2006;317:82–9. https://doi.org/10.1016/J.IJPHARM.2006.02.045 .

[14] Battaglia L, Serpe L, Foglietta F, Muntoni E, Gallarate M, Del Pozo Rodriguez A, et al. Application of lipid nanoparticles to ocular drug delivery. Expert Opin Drug Deliv 2016;13:1743–57. https://doi.org/10.1080/17425247.2016.1201059 .

[15] Sánchez-López E, Espina M, Doktorovova S, Souto EB, García ML. Lipid nanoparticles (SLN, NLC): Overcoming the anatomical and physiological barriers of the eye - Part II - Ocular drug-loaded lipid nanoparticles. Eur J Pharm Biopharm 2017;110:58–69. https://doi.org/10.1016/J.EJPB.2016.10.013 .

[16] Balguri SP, Adelli GR, Majumdar S. Topical ophthalmic lipid nanoparticle formulations (SLN, NLC) of indomethacin for delivery to the posterior segment ocular tissues. Eur J Pharm Biopharm 2016;109:224–35. https://doi.org/10.1016/J.EJPB.2016.10.015 .

[17] Araújo J, Gonzalez E, Egea MA, Garcia ML, Souto EB. Nanomedicines for ocular NSAIDs: safety on drug delivery. Nanomedicine 2009;5:394–401. https://doi.org/10.1016/J.NANO.2009.02.003 .

[18] Li X, Nie S fang, Kong J, Li N, Ju C yi, Pan W san. A controlled-release ocular delivery system for ibuprofen based on nanostructured lipid carriers. Int J Pharm 2008;363:177–82. https://doi.org/10.1016/J.IJPHARM.2008.07.017 .

[19] Almeida H, Amaral MH, Lobão P, Silva AC, Lobo JMS. Applications of polymeric and lipid nanoparticles in ophthalmic pharmaceutical formulations: present and future considerations. J Pharm Pharm Sci 2014;17:278–93. https://doi.org/10.18433/J3DP43 .

[20] Bandiwadekar A, Jose J, Gopan G, Augustin V, Ashtekar H, Khot KB. Transdermal delivery of resveratrol loaded solid lipid nanoparticle as a microneedle patch: a novel approach for the treatment of Parkinson's disease. Drug Delivery and Translational Research 2024 15:3 2024;15:1043–73. https://doi.org/10.1007/S13346-024-01656-0 .

[21] Akombaetwa N, Ilangala AB, Thom L, Memvanga PB, Witika BA, Buya AB. Current Advances in Lipid Nanosystems Intended for Topical and Transdermal Drug Delivery Applications. Pharmaceutics 2023;15:656. https://doi.org/10.3390/PHARMACEUTICS15020656 .

[22] Liu M, Wen J, Sharma M. Solid Lipid Nanoparticles for Topical Drug Delivery: Mechanisms, Dosage Form Perspectives, and Translational Status. Curr Pharm Des 2020;26:3203–17. https://doi.org/10.2174/1381612826666200526145706 .

[23] Hosseini M, Haji-Fatahaliha M, Jadidi-Niaragh F, Majidi J, Yousefi M. The use of nanoparticles as a promising therapeutic approach in cancer immunotherapy. Artif Cells Nanomed Biotechnol 2016;44:1051–61. https://doi.org/10.3109/21691401.2014.998830 .

[24] Ajorlou E, Khosroushahi AY. Trends on polymer- and lipid-based nanostructures for parenteral drug delivery to tumors. Cancer Chemother Pharmacol 2017;79:251–65. https://doi.org/10.1007/S00280-016-3168-6 .

[25] Joshi MD, Müller RH. Lipid nanoparticles for parenteral delivery of actives. Eur J Pharm Biopharm 2009;71:161–72. https://doi.org/10.1016/J.EJPB.2008.09.003 .

[26] Bhise K, Kashaw SK, Sau S, Iyer AK. Nanostructured lipid carriers employing polyphenols as promising anticancer agents: Quality by design (QbD) approach. Int J Pharm 2017;526:506–15. https://doi.org/10.1016/J.IJPHARM.2017.04.078 .

[27] Wissing SA, Kayser O, Müller RH. Solid lipid nanoparticles for parenteral drug delivery. Adv Drug Deliv Rev 2004;56:1257–72. https://doi.org/10.1016/j.addr.2003.12.002 .

[28] Pandita D, Kumar S, Poonia N, international VL-F research, 2014 undefined. Solid lipid nanoparticles enhance oral bioavailability of resveratrol, a natural polyphenol. ElsevierD Pandita, S Kumar, N Poonia, V LatherFood Research International, 2014•Elsevier n.d.

[29] Beloqui A, Solinís MA, Delgado A, Évora C, Isla A, Rodríguez-Gascón A. Fate of nanostructured lipid carriers (NLCs) following the oral route: design, pharmacokinetics and biodistribution. J Microencapsul 2014;31:1–8. https://doi.org/10.3109/02652048.2013.788090 .

[30] Rao S, Prestidge CA. Polymer-lipid hybrid systems: merging the benefits of polymeric and lipid-based nanocarriers to improve oral drug delivery. Expert Opin Drug Deliv 2016;13:691–707. https://doi.org/10.1517/17425247.2016.1151872 .

[31] Souto EB, Müller RH. Investigation of the factors influencing the incorporation of clotrimazole in SLN and NLC prepared by hot high-pressure homogenization. J Microencapsul 2006;23:377–88. https://doi.org/10.1080/02652040500435295 .

[32] Waleed O, Albasri A, Kumar V, Rajagopal MS. molecules Development of Computational In Silico Model for Nano Lipid Carrier Formulation of Curcumin 2023. https://doi.org/10.3390/molecules28041833 .

[33] Al-Mutairi AA, Alkhatib MH. Antitumour effects of a solid lipid nanoparticle loaded with gemcitabine and oxaliplatin on the viability, apoptosis, autophagy, and Hsp90 of ovarian cancer cells. J Microencapsul 2022;39:467–80. https://doi.org/10.1080/02652048.2022.2109218 .

[34] Pervaiz F, Saba A, Yasin H, Buabeid M, Noreen S, Khan AK, et al. Fabrication of solid lipid nanoparticles-based patches of paroxetine and their ex-vivo permeation behaviour. Artif Cells Nanomed Biotechnol 2023;51:108–19. https://doi.org/10.1080/21691401.2023.2179631 .

[35] Zhao W, Zeng M, Li K, Pi C, Liu Z, Zhan C, et al. Solid lipid nanoparticle as an effective drug delivery system of a novel curcumin derivative: formulation, release in vitro and pharmacokinetics in vivo. Pharm Biol 2022;60:2300–7. https://doi.org/10.1080/13880209.2022.2136205 .

[36] El-Refaie WM, Ghazy MS, Ateyya FA, Sheta E, Shafek MY, Ibrahim MS, et al. Rhein methotrexate-decorated solid lipid nanoparticles altering adjuvant arthritis progression through endoplasmic reticulum stress-mediated apoptosis. Inflammopharmacology 2023;31:3127–42. https://doi.org/10.1007/S10787-023-01295-W .

[37] de Abreu Martins HH, Turmo-Ibarz A, Hilsdorf Piccoli R, Martín-Belloso O, Salvia-Trujillo L. Influence of lipid nanoparticle physical state on β-carotene stability kinetics under different environmental conditions. Food Funct 2021;12:840–51. https://doi.org/10.1039/D0FO01980A .

[38] Lemasson O, Briançon S, Bourgeaux V, Guichard M, Valour JP, Moret GA, et al. Are Nanostructured Lipid Carriers (NLC) better than Solid Lipid Nanoparticles (SLN) for delivering abiraterone acetate through the gastrointestinal tract? Int J Pharm 2024;667. https://doi.org/10.1016/J.IJPHARM.2024.124869 .

[39] Akanda M, Getti G, Nandi U, Mithu MS, Douroumis D. Bioconjugated solid lipid nanoparticles (SLNs) for targeted prostate cancer therapy. Int J Pharm 2021;599. https://doi.org/10.1016/J.IJPHARM.2021.120416 .

[40] Zielińska A, da Ana R, Fonseca J, Szalata M, Wielgus K, Fathi F, et al. Phytocannabinoids: Chromatographic Screening of Cannabinoids and Loading into Lipid Nanoparticles. Molecules 2023;28. https://doi.org/10.3390/MOLECULES28062875 .

[41] Pinna N, Ianni F, Blasi F, Stefani A, Codini M, Sabatini S, et al. Unconventional Extraction of Total Non-Polar Carotenoids from Pumpkin Pulp and Their Nanoencapsulation. Molecules 2022;27. https://doi.org/10.3390/MOLECULES27238240 .

[42] Din F, Jin SG, Choi HG. Particle and Gel Characterization of Irinotecan-Loaded Double-Reverse Thermosensitive Hydrogel. Polymers (Basel) 2021;13:1–11. https://doi.org/10.3390/POLYM13040551 .

[43] Samee A, Usman F, Wani TA, Farooq M, Shah HS, Javed I, et al. Sulconazole-Loaded Solid Lipid Nanoparticles for Enhanced Antifungal Activity: In Vitro and In Vivo Approach. Molecules 2023;28. https://doi.org/10.3390/MOLECULES28227508 .

[44] El-Dakroury WA, Zewail MB, Asaad GF, Abdallah HMI, Shabana ME, Said AR, et al. Fexofenadine-loaded chitosan coated solid lipid nanoparticles (SLNs): A potential oral therapy for ulcerative colitis. Eur J Pharm Biopharm 2024;196. https://doi.org/10.1016/J.EJPB.2024.114205 .

[45] Landh E, Moir LM, Traini D, Young PM, Ong HX. Properties of rapamycin solid lipid nanoparticles for lymphatic access through the lungs & part II: the effect of nanoparticle charge. Nanomedicine (Lond) 2020;15:1947–63. https://doi.org/10.2217/NNM-2020-0192 .

[46] Rosita N, Sultani AA, Hariyadi DM. Penetration study of p-methoxycinnamic acid (PMCA) in nanostructured lipid carrier, solid lipid nanoparticles, and simple cream into the rat skin. Sci Rep 2022;12. https://doi.org/10.1038/S41598-022-23514-0 .

[47] Mulay L, Hegde N, Kanugo A. Formulation Optimization and Characterization of Solid Lipid Nanoparticles of Apixaban. Recent Pat Nanotechnol 2024;18. https://doi.org/10.2174/0118722105284862240506045944 .

[48] Singh M, Schiavone N, Papucci L, Maan P, Kaur J, Singh G, et al. Streptomycin sulphate loaded solid lipid nanoparticles show enhanced uptake in macrophage, lower MIC in Mycobacterium and improved oral bioavailability. Eur J Pharm Biopharm 2021;160:100–24. https://doi.org/10.1016/J.EJPB.2021.01.009 .

[49] Saini K, Modgill N, Singh KK, Kakkar V. Tetrahydrocurcumin Lipid Nanoparticle Based Gel Promotes Penetration into Deeper Skin Layers and Alleviates Atopic Dermatitis in 2,4-Dinitrochlorobenzene (DNCB) Mouse Model. Nanomaterials (Basel) 2022;12. https://doi.org/10.3390/NANO12040636 .

[50] Raja HN, Din F ud, Shabbir K, Khan S, Alamri AH, Al Awadh AA, et al. Sodium alginate-based smart gastro-retentive drug delivery system of revaprazan loaded SLNs; Formulation and characterization. Int J Biol Macromol 2023;253. https://doi.org/10.1016/J.IJBIOMAC.2023.127402 .

[51] Nadaf SJ, Killedar SG, Kumbar VM, Bhagwat DA, Gurav SS. Pazopanib-laden lipid based nanovesicular delivery with augmented oral bioavailability and therapeutic efficacy against non-small cell lung cancer. Int J Pharm 2022;628. https://doi.org/10.1016/J.IJPHARM.2022.122287 .

[52] Rasouliyan F, Eskandani M, Jaymand M, Akbari Nakhjavani S, Farahzadi R, Vandghanooni S, et al. Preparation, physicochemical characterization, and anti-proliferative properties of Lawsone-loaded solid lipid nanoparticles. Chem Phys Lipids 2021;239. https://doi.org/10.1016/J.CHEMPHYSLIP.2021.105123 .

[53] Khan MFA, Ur.rehman A, Howari H, Alhodaib A, Ullah F, Mustafa ZU, et al. Hydrogel Containing Solid Lipid Nanoparticles Loaded with Argan Oil and Simvastatin: Preparation, In Vitro and Ex Vivo Assessment. Gels 2022;8. https://doi.org/10.3390/GELS8050277 .

[54] Da Rocha MCO, Da Silva PB, Radicchi MA, Andrade BYG, De Oliveira JV, Venus T, et al. Docetaxel-loaded solid lipid nanoparticles prevent tumor growth and lung metastasis of 4T1 murine mammary carcinoma cells. J Nanobiotechnology 2020;18. https://doi.org/10.1186/S12951-020-00604-7 .

[55] Li M, Fang G, Zahid F, Saleem R, Ishrat G, Ali Z, et al. Co-delivery of paclitaxel and curcumin loaded solid lipid nanoparticles for improved targeting of lung cancer: In vitro and in vivo investigation. Heliyon 2024;10. https://doi.org/10.1016/J.HELIYON.2024.E30290 .

[56] El-Salamouni NS, Gowayed MA, Seiffein NL, Abdel- Moneim RA, Kamel MA, Labib GS. Valsartan solid lipid nanoparticles integrated hydrogel: A challenging repurposed use in the treatment of diabetic foot ulcer, in-vitro/in-vivo experimental study. Int J Pharm 2021;592. https://doi.org/10.1016/J.IJPHARM.2020.120091 .

[57] Zielińska A, Ferreira NR, Feliczak-Guzik A, Nowak I, Souto EB. Loading, release profile and accelerated stability assessment of monoterpenes-loaded solid lipid nanoparticles (SLN). Pharm Dev Technol 2020;25:832–44. https://doi.org/10.1080/10837450.2020.1744008 .

[58] Ibrahim UH, Devnarain N, Omolo CA, Mocktar C, Govender T. Biomimetic pH/lipase dual responsive vitamin-based solid lipid nanoparticles for on-demand delivery of vancomycin. Int J Pharm 2021;607. https://doi.org/10.1016/J.IJPHARM.2021.120960 .

[59] Amasya G, Ergin AD, Erkan Cakirci O, Ozçelikay AT, Sezgin Bayindir Z, Yuksel N. A study to enhance the oral bioavailability of s-adenosyl-l-methionine (SAMe): SLN and SLN nanocomposite particles. Chem Phys Lipids 2021;237. https://doi.org/10.1016/J.CHEMPHYSLIP.2021.105086 .

[60] Valizadeh A, Khaleghi AA, Roozitalab G, Osanloo M. High anticancer efficacy of solid lipid nanoparticles containing Zataria multiflora essential oil against breast cancer and melanoma cell lines. BMC Pharmacol Toxicol 2021;22. https://doi.org/10.1186/S40360-021-00523-9 .

[61] Topal GR, Mészáros M, Porkoláb G, Szecskó A, Polgár TF, Siklós L, et al. ApoE-Targeting Increases the Transfer of Solid Lipid Nanoparticles with Donepezil Cargo across a Culture Model of the Blood-Brain Barrier. Pharmaceutics 2020;13:1–19. https://doi.org/10.3390/PHARMACEUTICS13010038 .

[62] Saini S, Sharma T, Jain A, Kaur H, Katare OP, Singh B. Systematically designed chitosan-coated solid lipid nanoparticles of ferulic acid for effective management of Alzheimer's disease: A preclinical evidence. Colloids Surf B Biointerfaces 2021;205. https://doi.org/10.1016/J.COLSURFB.2021.111838 .

[63] Abd-Elghany AE, El-Garhy O, Fatease A Al, Alamri AH, Abdelkader H. Enhancing Oral Bioavailability of Simvastatin Using Uncoated and Polymer-Coated Solid Lipid Nanoparticles. Pharmaceutics 2024;16. https://doi.org/10.3390/PHARMACEUTICS16060763 .

[64] Ding L, Luo X, Xian Q, Zhu S, Wen W. Innovative Approaches to Fucoxanthin Delivery: Characterization and Bioavailability of Solid Lipid Nanoparticles with Eco-Friendly Ingredients and Enteric Coating. Int J Mol Sci 2024;25. https://doi.org/10.3390/IJMS252312825 .

[65] Okezue MA, Uche C, Adebola A, Byrn SR. A Quality by Design Approach for Optimizing Solid Lipid Nanoparticles of Bedaquiline for Improved Product Performance. AAPS PharmSciTech 2024;25. https://doi.org/10.1208/S12249-024-02873-Z .

[66] Nafee N, Gaber DM, Elzoghby AO, Helmy MW, Abdallah OY. Promoted Antitumor Activity of Myricetin against Lung Carcinoma Via Nanoencapsulated Phospholipid Complex in Respirable Microparticles. Pharm Res 2020;37. https://doi.org/10.1007/S11095-020-02794-Z .

[67] Gupta T, Singh J, Kaur S, Sandhu S, Singh G, Kaur IP. Enhancing Bioavailability and Stability of Curcumin Using Solid Lipid Nanoparticles (CLEN): A Covenant for Its Effectiveness. Front Bioeng Biotechnol 2020;8. https://doi.org/10.3389/FBIOE.2020.00879 .

[68] Said DE, Amer EI, Sheta E, Makled S, Diab HE, Arafa FM. Nano-Encapsulated Melatonin: A Promising Mucosal Adjuvant in Intranasal Immunization against Chronic Experimental T. gondii Infection. Trop Med Infect Dis 2022;7. https://doi.org/10.3390/TROPICALMED7120401 .

[69] Rawat M, Mishra A, Muthu M, Singh S. Development of Repaglinide Loaded Solid Lipid Nanocarrier: Selection of Fabrication Method. vol. 7. 2010.

[70] Ryan A, Patel P, Ratrey P, O'Connor PM, O'Sullivan J, Ross RP, et al. The development of a solid lipid nanoparticle (SLN)-based lacticin 3147 hydrogel for the treatment of wound infections. Drug Deliv Transl Res 2023;13:2407–23. https://doi.org/10.1007/S13346-023-01332-9.

[71] Ratrey P, Bhattacharya S, Coffey L, Thompson D, Hudson SP. Solid lipid nanoparticle formulation maximizes membrane-damaging efficiency of antimicrobial nisin Z peptide. Colloids Surf B Biointerfaces 2025;245:114255. https://doi.org/10.1016/J.COLSURFB.2024.114255 .

[72] Resende D, Costa Lima SA, Reis S. Nanoencapsulation approaches for oral delivery of vitamin A. Colloids Surf B Biointerfaces 2020;193:111121. https://doi.org/10.1016/J.COLSURFB.2020.111121 .

[73] Tahir MA, Ali ME, Lamprecht A. Nanoparticle formulations as recrystallization inhibitors in transdermal patches. Int J Pharm 2020;575. https://doi.org/10.1016/J.IJPHARM.2019.118886 .

[74] Neves AR, van der Putten L, Queiroz JF, Pinheiro M, Reis S. Transferrin-functionalized lipid nanoparticles for curcumin brain delivery. J Biotechnol 2021;331:108–17. https://doi.org/10.1016/J.JBIOTEC.2021.03.010 .

[75] Talarico L, Pepi S, Susino S, Leone G, Bonechi C, Consumi M, et al. Design and Optimization of Solid Lipid Nanoparticles Loaded with Triamcinolone Acetonide. Molecules 2023;28. https://doi.org/10.3390/MOLECULES28155747 .

[76] Aly S, El-Kamel AH, Sheta E, El-Habashy SE. Chondroitin/Lactoferrin-dual functionalized pterostilbene-solid lipid nanoparticles as targeted breast cancer therapy. Int J Pharm 2023;642. https://doi.org/10.1016/J.IJPHARM.2023.123163 .

[77] Vieira ACC, Chaves LL, Pinheiro M, Lima SC, Neto PJR, Ferreira D, et al. Lipid nanoparticles coated with chitosan using a one-step association method to target rifampicin to alveolar macrophages. Carbohydr Polym 2021;252. https://doi.org/10.1016/J.CARBPOL.2020.116978 .

[78] Boskabadi M, Saeedi M, Akbari J, Morteza-Semnani K, Hashemi SMH, Babaei A. Topical Gel of Vitamin A Solid Lipid Nanoparticles: A Hopeful Promise as a Dermal Delivery System. Adv Pharm Bull 2021;11:663–74. https://doi.org/10.34172/APB.2021.075 .

[79] Nazief AM, Hassaan PS, Khalifa HM, Sokar MS, El-Kamel AH. Lipid-Based Gliclazide Nanoparticles for Treatment of Diabetes: Formulation, Pharmacokinetics, Pharmacodynamics and Subacute Toxicity Study. Int J Nanomedicine 2020;15:1129–48. https://doi.org/10.2147/IJN.S235290 .

[80] Wang N, Gao X, Li M, Li Y, Sun M. Use of Solid Lipid Nanoparticles for the Treatment of Acute Acoustic Stress-Induced Cochlea Damage. J Nanosci Nanotechnol 2020;20:7412–8. https://doi.org/10.1166/JNN.2020.18522 .

[81] Granja A, Nunes C, Sousa CT, Reis S. Folate receptor-mediated delivery of mitoxantrone-loaded solid lipid nanoparticles to breast cancer cells. Biomed Pharmacother 2022;154. https://doi.org/10.1016/J.BIOPHA.2022.113525 .

[82] Ledinski M, Marić I, Štefanić PP, Ladan I, Mihalić KC, Jurkin T, et al. Synthesis and In Vitro Characterization of Ascorbyl Palmitate-Loaded Solid Lipid Nanoparticles. Polymers (Basel) 2022;14. https://doi.org/10.3390/POLYM14091751 .

[83] Amer Ridha A, Kashanian S, Rafipour R, Hemati Azandaryani A, Zhaleh H, Mahdavian E. A promising dual-drug targeted delivery system in cancer therapy: nanocomplexes of folate-apoferritin-conjugated cationic solid lipid nanoparticles. Pharm Dev Technol 2021;26:673–81. https://doi.org/10.1080/10837450.2021.1920037 .

[84] Han L, Ma X, Chen M, He J, Zhang W. Preparation, Characterization and In Vitro Anticancer Activity of Sulforaphene-Loaded Solid Lipid Nanoparticles. Foods 2024;13. https://doi.org/10.3390/FOODS13233898 .

[85] Abo-zalam HB, El-Denshary ES, Abdelsalam RM, Khalil IA, Khattab MM, Hamzawy MA. Therapeutic advancement of simvastatin-loaded solid lipid nanoparticles (SV-SLNs) in treatment of hyperlipidemia and attenuating hepatotoxicity, myopathy and apoptosis: Comprehensive study. Biomed Pharmacother 2021;139. https://doi.org/10.1016/J.BIOPHA.2021.111494 .

[86] Bevilacqua Rolfsen Ferreira da Silva G, Pereira das Neves S, Roque Oliveira SC, Marques F, Gomes de Oliveira A, de Lima Leite F, et al. Comparative effectiveness of preventive treatment with dimethyl fumarate-loaded solid lipid nanoparticles and oral dimethyl fumarate in a mouse model of multiple sclerosis. J Autoimmun 2022;132. https://doi.org/10.1016/J.JAUT.2022.102893 .

[87] Qin W, Quan G, Sun Y, Chen M, Yang P, Feng D, et al. Dissolving Microneedles with Spatiotemporally controlled pulsatile release Nanosystem for Synergistic Chemo-photothermal Therapy of Melanoma. Theranostics 2020;10:8179–96. https://doi.org/10.7150/THNO.44194 .

[88] Silva MI, Barbosa AI, Lima SAC, Costa P, Torres T, Reis S. Freeze-Dried Softisan® 649-Based Lipid Nanoparticles for Enhanced Skin Delivery of Cyclosporine A. Nanomaterials (Basel) 2020;10. https://doi.org/10.3390/NANO10050986 .

[89] Sreeharsha N, Prasanthi S, Rao GSNK, Gajula LR, Biradar N, Goudanavar P, et al. Formulation optimization of chitosan surface coated solid lipid nanoparticles of griseofulvin: A Box-Behnken design and in vivo pharmacokinetic study. Eur J Pharm Sci 2025;204. https://doi.org/10.1016/J.EJPS.2024.106951 .

[90] Schubert MA, Müller-Goymann CC. Solvent injection as a new approach for manufacturing lipid nanoparticles – evaluation of the method and process parameters. European Journal of Pharmaceutics and Biopharmaceutics 2003;55:125–31. https://doi.org/10.1016/S0939-6411(02)00130-3 .

[91] Jain AK, Jain A, Garg NK, Agarwal A, Jain A, Jain SA, et al. Adapalene loaded solid lipid nanoparticles gel: An effective approach for acne treatment. Colloids Surf B Biointerfaces 2014;121:222–9. https://doi.org/10.1016/j.colsurfb.2014.05.041 .

[92] Jain S, Jain SK, Khare P, Gulbake A, Bansal D, Jain SK. Design and development of solid lipid nanoparticles for topical delivery of an anti-fungal agent. Drug Deliv 2010;17:443–51. https://doi.org/10.3109/10717544.2010.483252 .

[93] Madan J, Dua K, Khude P. Development and evaluation of solid lipid nanoparticles of mometasone furoate for topical delivery. Int J Pharm Investig 2014;4:60. https://doi.org/10.4103/2230-973x.133047 .

[94] Mante PK, Adomako NO, Antwi P, Kusi-Boadum NK, Osafo N. Solid-lipid nanoparticle formulation improves antiseizure action of cryptolepine. Biomed Pharmacother 2021;137. https://doi.org/10.1016/J.BIOPHA.2021.111354 .

[95] Khan AS, Shah KU, Al Mohaini M, Alsalman AJ, Al Hawaj MA, Alhashem YN, et al. Tacrolimus-Loaded Solid Lipid Nanoparticle Gel: Formulation Development and In Vitro Assessment for Topical Applications. Gels 2022;8. https://doi.org/10.3390/GELS8020129 .

[96] Blanco-Llamero C, Galindo-Camacho RM, Fonseca J, Santini A, Señoráns FJ, Souto EB. Development of Lipid Nanoparticles Containing Omega-3-Rich Extract of Microalga Nannochlorpsis gaditana. Foods 2022;11. https://doi.org/10.3390/FOODS11233749 .

[97] Ibrahim SS. Nanostructured Lipid Carriers for Oral Delivery of a Corticosteroid: Role of Formulation on Biopharmaceutical Performance. J Pharm Sci 2023;112:790–7. https://doi.org/10.1016/J.XPHS.2022.10.014 .

[98] Mante PK, Adomako NO, Antwi P, Kusi-Boadum NK. Chronic administration of cryptolepine nanoparticle formulation alleviates seizures in a neurocysticercosis model. Current Research in Pharmacology and Drug Discovery 2021;2. https://doi.org/10.1016/J.CRPHAR.2021.100040 .

[99] Lv C, Li H, Cui H, Bi Q, Wang M. Solid lipid nanoparticle delivery of rhynchophylline enhanced the efficiency of allergic asthma treatment via the upregulation of suppressor of cytokine signaling 1 by repressing the p38 signaling pathway. Bioengineered 2021;12:8635–49. https://doi.org/10.1080/21655979.2021.1988364 .

[100] Hasan N, Imran M, Kesharwani P, Khanna K, Karwasra R, Sharma N, et al. Intranasal delivery of Naloxone-loaded solid lipid nanoparticles as a promising simple and non-invasive approach for the management of opioid overdose. Int J Pharm 2021;599. https://doi.org/10.1016/J.IJPHARM.2021.120428 .

[101] De K. Decapeptide Modified Doxorubicin Loaded Solid Lipid Nanoparticles as Targeted Drug Delivery System against Prostate Cancer. Langmuir 2021;37:13194–207. https://doi.org/10.1021/ACS.LANGMUIR.1C01370 .

[102] Landh E, M Moir L, Bradbury P, Traini D, M Young P, Ong HX. Properties of rapamycin solid lipid nanoparticles for lymphatic access through the lungs & part I: the effect of size. Nanomedicine (Lond) 2020;15:1927–45. https://doi.org/10.2217/NNM-2020-0077 .

[103] Pareek A, Kothari R, Pareek A, Ratan Y, Kashania P, Jain V, et al. Development of a new inhaled swellable microsphere system for the dual delivery of naringenin-loaded solid lipid nanoparticles and doxofylline for the treatment of asthma. Eur J Pharm Sci 2024;193. https://doi.org/10.1016/J.EJPS.2023.106642 .

[104] Weerapol Y, Manmuan S, Chaothanaphat N, Limmatvapirat S, Sirirak J, Tamdee P, et al. New Approach for Preparing Solid Lipid Nanoparticles with Volatile Oil-Loaded Quercetin Using the Phase-Inversion Temperature Method. Pharmaceutics 2022;14. https://doi.org/10.3390/PHARMACEUTICS14101984 .

[105] Sarheed O, Shouqair D, Ramesh K, Amin M, Boateng J, Drechsler M. Physicochemical characteristics and in vitro permeation of loratadine solid lipid nanoparticles for transdermal delivery. Ther Deliv 2020;11:685–700. https://doi.org/10.4155/TDE-2020-0075 .

[106] Torrisi C, Cardullo N, Russo S, La Mantia A, Acquaviva R, Muccilli V, et al. Benzo[k,l]xanthene Lignan-Loaded Solid Lipid Nanoparticles for Topical Application: A Preliminary Study. Molecules 2022;27. https://doi.org/10.3390/MOLECULES27185887 .

[107] Date of Patent: 11) 45) (54) (76) (21) 22 (51) (52) (58) (56) METHOD FOR PRODUCING SOLID LIPID MICROSPHERES HAVING ANARROWSIZE. 1993.

[108] Shah RM, Malherbe F, Eldridge D, Palombo EA, Harding IH. Physicochemical characterization of solid lipid nanoparticles (SLNs) prepared by a novel microemulsion technique. J Colloid Interface Sci 2014;428:286–94. https://doi.org/10.1016/j.jcis.2014.04.057 .

[109] Bondì ML, Fontana G, Carlisi B, Giammona G. Preparation and Characterization of Solid Lipid Nanoparticles Containing Cloricromene. Drug Delivery: Journal of Delivery and Targeting of Therapeutic Agents 2003;10:245–50. https://doi.org/10.1080/drd_10_4_245 .

[110] Zhou P, Yan B, Wei B, Fu L, Wang Y, Wang W, et al. Quercetin-solid lipid nanoparticle-embedded hyaluronic acid functionalized hydrogel for immunomodulation to promote bone reconstruction. Regen Biomater 2023;10. https://doi.org/10.1093/RB/RBAD025 .

[111] Kim MH, Jeon YE, Kang S, Lee JY, Lee KW, Kim KT, et al. Lipid Nanoparticles for Enhancing the Physicochemical Stability and Topical Skin Delivery of Orobol. Pharmaceutics 2020;12:1–16. https://doi.org/10.3390/PHARMACEUTICS12090845 .

[112] Yeo S, Wu H, Yoon I, Kim HS, Song YK, Lee WK. Enhanced Photodynamic Therapy Efficacy through Solid Lipid Nanoparticle of Purpurin-18-N-Propylimide Methyl Ester for Cancer Treatment. Int J Mol Sci 2024;25. https://doi.org/10.3390/IJMS251910382 .

[113] Ortega Martínez E, Morales Hernández ME, Castillo-González J, González-Rey E, Ruiz Martínez MA. Dopamine-loaded chitosan-coated solid lipid nanoparticles as a promise nanocarriers to the CNS. Neuropharmacology 2024;249. https://doi.org/10.1016/J.NEUROPHARM.2024.109871 .

[114] Trombino S, Malivindi R, Barbarossa G, Sole R, Curcio F, Cassano R. Solid Lipid Nanoparticles Hydroquinone-Based for the Treatment of Melanoma: Efficacy and Safety Studies. Pharmaceutics 2023;15. https://doi.org/10.3390/PHARMACEUTICS15051375 .

[115] Zhang H, Guo J, Wang Z, Wang N, Feng N, Zhang Y. Diethylene glycol monoethyl ether-mediated nanostructured lipid carriers enhance trans-ferulic acid delivery by Caco-2 cells superior to solid lipid nanoparticles. Acta Pharm 2023;73:133–43. https://doi.org/10.2478/ACPH-2023-0009 .

[116] Sharma S, Goel V, Kaur P, Gadhave K, Garg N, Das Singla L, et al. Targeted drug delivery using beeswax-derived albendazole-loaded solid lipid nanoparticles in Haemonchus contortus, an albendazole-tolerant nematode. Exp Parasitol 2023;253. https://doi.org/10.1016/J.EXPPARA.2023.108593 .

[117] Burki FA, Shah KU, Razaque G, Shah SU, Nawaz A, Saeed MD, et al. Optimization of Chitosan-Decorated Solid Lipid Nanoparticles for Improved Flurbiprofen Transdermal Delivery. ACS Omega 2023;8:19302–10. https://doi.org/10.1021/ACSOMEGA.2C08135 .

[118] Cometa S, Bonifacio MA, Trapani G, Di Gioia S, Dazzi L, De Giglio E, et al. In vitro investigations on dopamine loaded Solid Lipid Nanoparticles. J Pharm Biomed Anal 2020;185. https://doi.org/10.1016/J.JPBA.2020.113257 .

[119] Khatak S, Mehta M, Awasthi R, Paudel KR, Singh SK, Gulati M, et al. Solid lipid nanoparticles containing anti-tubercular drugs attenuate the Mycobacterium marinum infection. Tuberculosis (Edinb) 2020;125. https://doi.org/10.1016/J.TUBE.2020.102008 .

[120] Ryan A, Patel P, O'Connor PM, Cookman J, Ross RP, Hill C, et al. Single versus double occupancy solid lipid nanoparticles for delivery of the dual-acting bacteriocin, lacticin 3147. Eur J Pharm Biopharm 2022;176:199–210. https://doi.org/10.1016/J.EJPB.2022.05.016 .

[121] Alhelal HM, Mehta S, Kadian V, Kakkar V, Tanwar H, Rao R, et al. Solid Lipid Nanoparticles Embedded Hydrogels as a Promising Carrier for Retarding Irritation of Leflunomide. Gels 2023;9. https://doi.org/10.3390/GELS9070576 .

[122] Bustos Araya ME, Nardi-Ricart A, Calpena Capmany AC, Miñarro Carmona M. Chondroitin Sulfate for Cartilage Regeneration, Administered Topically Using a Nanostructured Formulation. Int J Mol Sci 2024;25. https://doi.org/10.3390/IJMS251810023 .

[123] Wang W, Zhou M, Xu Y, Peng W, Zhang S, Li R, et al. Resveratrol-Loaded TPGS-Resveratrol-Solid Lipid Nanoparticles for Multidrug-Resistant Therapy of Breast Cancer: In Vivo and In Vitro Study. Front Bioeng Biotechnol 2021;9. https://doi.org/10.3389/FBIOE.2021.762489 .

[124] Kaur R, Shaikh TB, Priya Sripadi H, Kuncha M, Vijaya Sarathi UVR, Kulhari H, et al. Nintedanib solid lipid nanoparticles improve oral bioavailability and ameliorate pulmonary fibrosis in vitro and

in vivo models. Int J Pharm 2024;649. https://doi.org/10.1016/J.IJPHARM.2023.123644 .

[125] Zhang Z, Pan T, Zhao Y, Ren M, Li Y, Lu G, et al. Topotecan-loaded thermosensitive nanocargo for tumor therapy: In vitro and in vivo analyses. Int J Pharm 2021;606. https://doi.org/10.1016/J.IJPHARM.2021.120871 .

[126] Ahmed T, Shanthi N, Mahato AK. Amorolfine hydrochloride loaded solid lipid nanoparticles: Preparation, characterization and ex vivo nail permeation study to treat onychomycosis. Ann Pharm Fr 2024. https://doi.org/10.1016/J.PHARMA.2024.12.002 .

[127] Pires VC, Magalhães CP, Ferrante M, Rebouças J de S, Nguewa P, Severino P, et al. Solid lipid nanoparticles as a novel formulation approach for tanespimycin (17-AAG) against leishmania infections: Preparation, characterization and macrophage uptake. Acta Trop 2020;211. https://doi.org/10.1016/J.ACTATROPICA.2020.105595 .

[128] Moez NM, Hosseini SM, kalhori F, Shokoohizadeh L, Arabestani MR. Co-delivery of streptomycin and hydroxychloroquine by labeled solid lipid nanoparticles to treat brucellosis: an animal study. Sci Rep 2023;13. https://doi.org/10.1038/S41598-023-41150-0 .

[129] El-Telbany DFA, El-Telbany RFA, Zakaria S, Ahmed KA, El-Feky YA. Formulation and assessment of hydroxyzine HCL solid lipid nanoparticles by dual emulsification technique for transdermal delivery. Biomed Pharmacother 2021;143. https://doi.org/10.1016/J.BIOPHA.2021.112130 .

[130] Bosca F, Foglietta F, Gimenez A, Canaparo R, Durando G, Andreana I, et al. Exploiting Lipid and Polymer Nanocarriers to Improve the Anticancer Sonodynamic Activity of Chlorophyll. Pharmaceutics 2020;12:1–21. https://doi.org/10.3390/PHARMACEUTICS12070605 .

[131] Liang Z, Zhang Z, Lu P, Yang J, Han L, Liu S, et al. The effect of charges on the corneal penetration of solid lipid nanoparticles loaded Econazole after topical administration in rabbits. Eur J Pharm Sci 2023;187. https://doi.org/10.1016/J.EJPS.2023.106494.

[132] Qin L, Lu T, Qin Y, He Y, Cui N, Du A, et al. In Vivo Effect of Resveratrol-Loaded Solid Lipid Nanoparticles to Relieve Physical Fatigue for Sports Nutrition Supplements. Molecules 2020;25. https://doi.org/10.3390/MOLECULES25225302 .

[133] Buzyurova DN, Pashirova TN, Zueva I V., Burilova EA, Shaihutdinova ZM, Rizvanov IK, et al. Surface modification of pralidoxime chloride-loaded solid lipid nanoparticles for enhanced brain reactivation of organophosphorus-inhibited AChE: Pharmacokinetics in rat. Toxicology 2020;444. https://doi.org/10.1016/J.TOX.2020.152578 .

[134] Maretti E, Molinari S, Battini R, Rustichelli C, Truzzi E, Iannuccelli V, et al. Design, Characterization, and In Vitro Assays on Muscle Cells of Endocannabinoid-like Molecule Loaded Lipid Nanoparticles for a Therapeutic Anti-Inflammatory Approach to Sarcopenia. Pharmaceutics 2022;14. https://doi.org/10.3390/PHARMACEUTICS14030648 .

[135] Kaushik L, Srivastava S, Panjeta A, Chaudhari D, Ghadi R, Kuche K, et al. Exploration of docetaxel palmitate and its solid lipid nanoparticles as a novel option for alleviating the rising concern of multi-drug resistance. Int J Pharm 2020;578. https://doi.org/10.1016/J.IJPHARM.2020.119088 .

[136] Shewale H, Kanugo A. Sustained release of Ambrisentan solid lipid nanoparticles for the treatment of hypertension: Melt emulsification method. Ann Pharm Fr 2025. https://doi.org/10.1016/J.PHARMA.2025.01.003 .

[137] Glaubitt K, Ricci M, Giovagnoli S. Exploring the Nano Spray-Drying Technology as an Innovative Manufacturing Method for Solid Lipid Nanoparticle Dry Powders. AAPS PharmSciTech 2019;20. https://doi.org/10.1208/S12249-018-1203-0 .

[138] Trotta M, Cavalli R, Trotta C, Bussano R, Costa L. Electrospray technique for solid lipid-based particle production. Drug Dev Ind Pharm 2010;36:431–8. https://doi.org/10.3109/03639040903241817 .

[139] Freitas C, Müller RH. Spray-drying of solid lipid nanoparticles (SLN(TM)). European Journal of Pharmaceutics and Biopharmaceutics 1998;46:145–51. https://doi.org/10.1016/S0939-6411(97)00172-0 .

[140] Sohail S, Shah FA, Zaman S uz, Almari AH, Malik I, Khan SA, et al. Melatonin delivered in solid lipid nanoparticles ameliorated its neuroprotective effects in cerebral ischemia. Heliyon 2023;9. https://doi.org/10.1016/J.HELIYON.2023.E19779 .

[141] Zhou K, Yan Y, Chen D, Huang L, Li C, Meng K, et al. Solid Lipid Nanoparticles for Duodenum Targeted Oral Delivery of Tilmicosin. Pharmaceutics 2020;12:1–19. https://doi.org/10.3390/PHARMACEUTICS12080731 .

[142] Rai N, Madni A, Faisal A, Jamshaid T, Khan MI, Khan MM, et al. Glyceryl Monostearate based Solid Lipid Nanoparticles for Controlled Delivery of Docetaxel. Curr Drug Deliv 2021;18:1368–76. https://doi.org/10.2174/1567201818666210203180153 .

[143] He Y, Zhan C, Pi C, Zuo Y, Yang S, Hu M, et al. Enhanced Oral Bioavailability of Felodipine from Solid Lipid Nanoparticles Prepared Through Effervescent Dispersion Technique. AAPS PharmSciTech 2020;21. https://doi.org/10.1208/S12249-020-01711-2 .

[144] Saad S, Ahmad I, Kawish SM, Khan UA, Ahmad FJ, Ali A, et al. Improved cardioprotective effects of hesperidin solid lipid nanoparticles prepared by supercritical antisolvent technology. Colloids Surf B Biointerfaces 2020;187. https://doi.org/10.1016/J.COLSURFB.2019.110628 .

[145] Weaver E, Sommonte F, Hooker A, Denora N, Uddin S, Lamprou DA. Microfluidic encapsulation of enzymes and steroids within solid lipid nanoparticles. Drug Deliv Transl Res 2024;14:266–79. https://doi.org/10.1007/S13346-023-01398-5 .

[146] Bera H, Zhao C, Tian X, Cun D, Yang M. Mannose-Decorated Solid-Lipid Nanoparticles for Alveolar Macrophage Targeted Delivery of Rifampicin. Pharmaceutics 2024;16. https://doi.org/10.3390/PHARMACEUTICS16030429 .

[147] Dutta RS, Elhassan GO, Devi TB, Bhattacharjee B, Singh M, Jana BK, et al. Enhanced efficacy of β-carotene loaded solid lipid nanoparticles optimized and developed via central composite design on breast cancer cell lines. Heliyon 2024;10. https://doi.org/10.1016/J.HELIYON.2024.E28457 .

[148] Li K, Pi C, Wen J, He Y, Yuan J, Shen H, et al. Formulation of the novel structure curcumin derivative-loaded solid lipid nanoparticles: synthesis, optimization, characterization and anti-tumor activity screening in vitro. Drug Deliv 2022;29:2044–57. https://doi.org/10.1080/10717544.2022.2092235 .

[149] Adeyemi SA, Az-Zamakhshariy Z, Choonara YE. In Vitro Prototyping of a Nano-Organogel for Thermo-Sonic Intra-Cervical Delivery of 5-Fluorouracil-Loaded Solid Lipid Nanoparticles for Cervical Cancer. AAPS PharmSciTech 2023;24. https://doi.org/10.1208/S12249-023-02583-Y .

[150] Subroto E, Andoyo R, Indiarto R, Wulandari E, Wadhiah EFN. Preparation of Solid Lipid Nanoparticle-Ferrous Sulfate by Double Emulsion Method Based on Fat Rich in Monolaurin and Stearic Acid. Nanomaterials (Basel) 2022;12. https://doi.org/10.3390/NANO12173054 .

[151] Wang J, Wang H, Xu H, Li J, Zhang X, Zhang X. Solid lipid nanoparticles as an effective sodium aescinate delivery system: formulation and anti-inflammatory activity. RSC Adv 2022;12:6583–91. https://doi.org/10.1039/D1RA07638H .

[152] Pinheiro RGR, Granja A, Loureiro JA, Pereira MC, Pinheiro M, Neves AR, et al. Quercetin lipid nanoparticles functionalized with transferrin for Alzheimer's disease. Eur J Pharm Sci 2020;148. https://doi.org/10.1016/J.EJPS.2020.105314 .

[153] Zhou Q, Hou K, Fu Z. Transferrin-Modified Mangiferin-Loaded SLNs: Preparation, Characterization, and Application in A549 Lung Cancer Cell. Drug Des Devel Ther 2022;16:1767–78. https://doi.org/10.2147/DDDT.S366531 .

[154] Helal SH, Abdel-Aziz HMM, El-Zayat MM, Hasaneen MNA. Preparation, characterization and properties of three different nanomaterials either alone or loaded with nystatin or fluconazole

antifungals. Sci Rep 2022;12. https://doi.org/10.1038/S41598-022-26523-1 .

[155] Satyanarayana SD, Abu Lila AS, Moin A, Moglad EH, Khafagy ES, Alotaibi HF, et al. Ocular Delivery of Bimatoprost-Loaded Solid Lipid Nanoparticles for Effective Management of Glaucoma. Pharmaceuticals (Basel) 2023;16. https://doi.org/10.3390/PH16071001 .

[156] Karamchedu S, Tunki L, Kulhari H, Pooja D. Morin hydrate loaded solid lipid nanoparticles: Characterization, stability, anticancer activity, and bioavailability. Chem Phys Lipids 2020;233. https://doi.org/10.1016/J.CHEMPHYSLIP.2020.104988 .

[157] Xu W, Deng Z, Xiang Y, Zhu D, Yi D, Mo Y, et al. Preparation, Characterization and Pharmacokinetics of Tolfenamic Acid-Loaded Solid Lipid Nanoparticles. Pharmaceutics 2022;14. https://doi.org/10.3390/PHARMACEUTICS14091929 .

[158] Paul PK, Nakpheng T, Paliwal H, Prem Ananth K, Srichana T. Inhalable solid lipid nanoparticles of levofloxacin for potential tuberculosis treatment. Int J Pharm 2024;660. https://doi.org/10.1016/J.IJPHARM.2024.124309 .

[159] Jagdale S, Narwade M, Sheikh A, Md S, Salve R, Gajbhiye V, et al. GLUT1 transporter-facilitated solid lipid nanoparticles loaded with anti-cancer therapeutics for ovarian cancer targeting. Int J Pharm 2023;637. https://doi.org/10.1016/J.IJPHARM.2023.122894 .

[160] Liakopoulou A, Mourelatou E, Hatziantoniou S. Exploitation of traditional healing properties, using the nanotechnology's advantages: The case of curcumin. Toxicol Rep 2021;8:1143–55. https://doi.org/10.1016/J.TOXREP.2021.05.012 .

[161] Yu Y, Chen D, Lee YY, Chen N, Wang Y, Qiu C. Physicochemical and In Vitro Digestion Properties of Curcumin-Loaded Solid Lipid Nanoparticles with Different Solid Lipids and Emulsifiers. Foods 2023;12. https://doi.org/10.3390/FOODS12102045 .

[162] Ak G, Ünal A, Karakayalı T, Özel B, Selvi Günel N, Hamarat Şanlıer Ş. Brain-targeted, drug-loaded solid lipid nanoparticles against glioblastoma cells in culture. Colloids Surf B Biointerfaces 2021;206. https://doi.org/10.1016/J.COLSURFB.2021.111946 .

[163] Pinheiro RGR, Granja A, Loureiro JA, Pereira MC, Pinheiro M, Neves AR, et al. RVG29-Functionalized Lipid Nanoparticles for Quercetin Brain Delivery and Alzheimer's Disease. Pharm Res 2020;37. https://doi.org/10.1007/S11095-020-02865-1 .

[164] De Gaetano F, Celesti C, Paladini G, Venuti V, Cristiano MC, Paolino D, et al. Solid Lipid Nanoparticles Containing Morin: Preparation, Characterization, and Ex Vivo Permeation Studies. Pharmaceutics 2023;15. https://doi.org/10.3390/PHARMACEUTICS15061605 .

[165] Tan X, Hao Y, Ma N, Yang Y, Jin W, Meng Y, et al. M6P-modified solid lipid nanoparticles loaded with matrine for the treatment of fibrotic liver. Drug Deliv 2023;30. https://doi.org/10.1080/10717544.2023.2219432 .

[166] Bharti Sharma J, Bhatt S, Tiwari A, Tiwari V, Kumar M, Verma R, et al. Statistical optimization of tetrahydrocurcumin loaded solid lipid nanoparticles using Box Behnken design in the management of streptozotocin-induced diabetes mellitus. Saudi Pharm J 2023;31. https://doi.org/10.1016/J.JSPS.2023.101727 .

[167] Arduino I, Liu Z, Rahikkala A, Figueiredo P, Correia A, Cutrignelli A, et al. Preparation of cetyl palmitate-based PEGylated solid lipid nanoparticles by microfluidic technique. Acta Biomater 2021;121:566–78. https://doi.org/10.1016/J.ACTBIO.2020.12.024 .

[168] Shahraki O, Shayganpour M, Hashemzaei M, Daneshmand S. Solid lipid nanoparticles (SLNs), the potential novel vehicle for enhanced in vivo efficacy of hesperidin as an anti-inflammatory agent. Bioorg Chem 2023;131. https://doi.org/10.1016/J.BIOORG.2022.106333 .

[169] Reczyńska-kolman K, Hartman K, Kwiecień K, Brzychczy-włoch M, Pamuła E. Composites Based on Gellan Gum, Alginate and Nisin-Enriched Lipid Nanoparticles for the Treatment of Infected Wounds. Int J Mol Sci 2021;23. https://doi.org/10.3390/IJMS23010321 .

[170] Uner B, Ozdemir S, Tas C, Uner M, Ozsoy Y. Loteprednol-Loaded Nanoformulations for Corneal Delivery by Quality-by-Design Concepts: Optimization, Characterization, and Anti-inflammatory Activity. AAPS PharmSciTech 2023;24. https://doi.org/10.1208/S12249-023-02551-6 .

[171] Abou-Taleb HA, Fathalla Z, Naguib DM, Fatease A Al, Abdelkader H. Chitosan/Solid-Lipid Nanoparticles Hybrid Gels for Vaginal Delivery of Estradiol for Management of Vaginal Menopausal Symptoms. Pharmaceuticals (Basel) 2023;16. https://doi.org/10.3390/PH16091284 .

[172] Rao H, Ahmad S, Madni A, Rao I, Ghazwani M, Hani U, et al. Compritol-Based Alprazolam Solid Lipid Nanoparticles for Sustained Release of Alprazolam: Preparation by Hot Melt Encapsulation. Molecules 2022;27. https://doi.org/10.3390/MOLECULES27248894 .

[173] Cristelo C, Sá AF, Lúcio M, Sarmento B, Gama FM. Vitamin D loaded into lipid nanoparticles shows insulinotropic effect in INS-1E cells. Eur J Pharm Sci 2024;196. https://doi.org/10.1016/J.EJPS.2024.106758 .

[174] Zhang Y, Wang L, Wang ZD, Zhou Q, Zhou X, Zhou T, et al. Surface-anchored microbial enzyme-responsive solid lipid nanoparticles enabling colonic budesonide release for ulcerative colitis treatment. J Nanobiotechnology 2023;21. https://doi.org/10.1186/S12951-023-01889-0 .

[175] Lima TLC, Souza LBFC, Tavares-Pessoa LCS, Dos Santos-Silva AM, Cavalcante RS, de Araújo-Júnior RF, et al. Phytol-Loaded Solid Lipid Nanoparticles as a Novel Anticandidal Nanobiotechnological Approach. Pharmaceutics 2020;12:1–19. https://doi.org/10.3390/PHARMACEUTICS12090871 .

[176] Surapaneni SG, Ambade A V. Poly(N-vinylcaprolactam) containing solid lipid polymer hybrid nanoparticles for controlled delivery of a hydrophilic drug gemcitabine hydrochloride. RSC Adv 2022;12:17621–8. https://doi.org/10.1039/D2RA02845J .

[177] Pawłowska M, Marzec M, Jankowiak W, Nowak I. Solid Lipid Nanoparticles Incorporated with Retinol and Pentapeptide-18-Optimization, Characterization, and Cosmetic Application. Int J Mol Sci 2024;25. https://doi.org/10.3390/IJMS251810078 .

[178] Alcantara KP, Malabanan JWT, Nalinratana N, Thitikornpong W, Rojsitthisak P, Rojsitthisak P. Cannabidiol-Loaded Solid Lipid Nanoparticles Ameliorate the Inhibition of Proinflammatory Cytokines and Free Radicals in an In Vitro Inflammation-Induced Cell Model. Int J Mol Sci 2024;25. https://doi.org/10.3390/IJMS25094744 .

[179] Pitzanti G, Rosa A, Nieddu M, Valenti D, Pireddu R, Lai F, et al. Transcutol® P Containing SLNs for Improving 8-Methoxypsoralen Skin Delivery. Pharmaceutics 2020;12:1–14. https://doi.org/10.3390/PHARMACEUTICS12100973 .

[180] Agrawal YO, Husain M, Patil KD, Sodgir V, Patil TS, Agnihotri V V., et al. Verapamil hydrochloride loaded solid lipid nanoparticles: Preparation, optimization, characterisation, and assessment of cardioprotective effect in experimental model of myocardial infarcted rats. Biomed Pharmacother 2022;154. https://doi.org/10.1016/J.BIOPHA.2022.113429 .

[181] Khaleseh F, Barzegar-Jalali M, Zakeri-Milani P, Karami Z, Zanjani MRS, Valizadeh H. How do lipid-based drug delivery systems affect the pharmacokinetic and tissue distribution of amiodarone? A comparative study of liposomes, solid lipid nanoparticles, and nanoemulsions. Iran J Basic Med Sci 2024;27:857–67. https://doi.org/10.22038/IJBMS.2024.75152.16292 .

[182] Ramadan AE hakim, Elsayed MMA, Elsayed A, Fouad MA, Mohamed MS, Lee S, et al. Development and optimization of vildagliptin solid lipid nanoparticles loaded ocuserts for controlled ocular delivery: A promising approach towards treating diabetic retinopathy. Int J Pharm X 2024;7. https://doi.org/10.1016/J.IJPX.2024.100232 .

[183] Gaber DM, Ibrahim SS, Awaad AK, Shahine YM, Elmallah S, Barakat HS, et al. A drug repurposing approach of Atorvastatin

calcium for its antiproliferative activity for effective treatment of breast cancer: In vitro and in vivo assessment. Int J Pharm X 2024;7. https://doi.org/10.1016/J.IJPX.2024.100249 .

[184] Ebrahimi H, Kazem Nezhad S, Farmoudeh A, Babaei A, Ebrahimnejad P, Akbari E, et al. Design and optimization of metformin-loaded solid lipid nanoparticles for neuroprotective effects in a rat model of diffuse traumatic brain injury: A biochemical, behavioral, and histological study. Eur J Pharm Biopharm 2022;181:122–35. https://doi.org/10.1016/J.EJPB.2022.10.018 .

[185] Gomes Souza L, Antonio Sousa-Junior A, Alves Santana Cintra B, Vieira dos Anjos JL, Leite Nascimento T, Palmerston Mendes L, et al. Pre-clinical safety of topically administered sunitinib-loaded lipid and polymeric nanocarriers targeting corneal neovascularization. Int J Pharm 2023;635. https://doi.org/10.1016/J.IJPHARM.2023.122682 .

[186] Sherif AY, Harisa GI, Alanazi FK, Nasr FA, Alqahtani AS. PEGylated SLN as a Promising Approach for Lymphatic Delivery of Gefitinib to Lung Cancer. Int J Nanomedicine 2022;17:3287–311. https://doi.org/10.2147/IJN.S365974 .

[187] Khezri K, Saeedi M, Morteza-Semnani K, Akbari J, Rostamkalaei SS. An emerging technology in lipid research for targeting hydrophilic drugs to the skin in the treatment of hyperpigmentation disorders: kojic acid-solid lipid nanoparticles. Artif Cells Nanomed Biotechnol 2020;48:841–53. https://doi.org/10.1080/21691401.2020.1770271 .

[188] Shahraeini SS, Akbari J, Saeedi M, Morteza-Semnani K, Abootorabi S, Dehghanpoor M, et al. Atorvastatin Solid Lipid Nanoparticles as a Promising Approach for Dermal Delivery and an Anti-inflammatory Agent. AAPS PharmSciTech 2020;21. https://doi.org/10.1208/S12249-020-01807-9 .

[189] Sabry SA, Abd El Razek AM, Nabil M, Khedr SM, El-Nahas HM, Eissa NG. Brain-targeted delivery of Valsartan using solid lipid nanoparticles labeled with Rhodamine B; a promising technique for mitigating the negative effects of stroke. Drug Deliv 2023;30. https://doi.org/10.1080/10717544.2023.2179127 .

[190] Raut P, Gambhire M, Panchal D, Gambhire V. Development and Optimization of Mirabegron Solid Lipid Nanoparticles as an Oral Drug Delivery for Overactive Bladder. Pharm Nanotechnol 2021;9:120–9. https://doi.org/10.2174/2211738509666210127143107 .

[191] Alves da Silva BT, Silva Lautenschlager S de O, Nakamura CV, Ximenes VF, Ogawa Y, Michel R, et al. Design of solid lipid nanoparticles for skin photoprotection through the topical delivery of caffeic acid-phthalimide. Int J Pharm 2025;669:125010. https://doi.org/10.1016/J.IJPHARM.2024.125010 .

[192] Parvez S, Yadagiri G, Gedda MR, Singh A, Singh OP, Verma A, et al. Modified solid lipid nanoparticles encapsulated with Amphotericin B and Paromomycin: an effective oral combination against experimental murine visceral leishmaniasis. Scientific Reports 2020 10:1 2020;10:1–14. https://doi.org/10.1038/s41598-020-69276-5 .

[193] Akel H, Csóka I, Ambrus R, Bocsik A, Gróf I, Mészáros M, et al. In Vitro Comparative Study of Solid Lipid and PLGA Nanoparticles Designed to Facilitate Nose-to-Brain Delivery of Insulin. Int J Mol Sci 2021;22. https://doi.org/10.3390/IJMS222413258 .

[194] Pi C, Zhao W, Zeng M, Yuan J, Shen H, Li K, et al. Anti-lung cancer effect of paclitaxel solid lipid nanoparticles delivery system with curcumin as co-loading partner in vitro and in vivo. Drug Deliv 2022;29:1878–91. https://doi.org/10.1080/10717544.2022.2086938 .

[195] Najib Ullah SNM, Afzal O, Altamimi ASA, Alossaimi MA, Almalki WH, Alzahrani A, et al. Bedaquiline-Loaded Solid Lipid Nanoparticles Drug Delivery in the Management of Non-Small-Cell Lung Cancer (NSCLC). Pharmaceuticals (Basel) 2023;16. https://doi.org/10.3390/PH16091309 .

[196] Hassan H, Adam SK, Alias E, Affandi MMRMM, Shamsuddin AF, Basir R. Central Composite Design for Formulation and Optimization of Solid Lipid Nanoparticles to Enhance Oral Bioavailability of Acyclovir. Molecules 2021;26. https://doi.org/10.3390/MOLECULES26185432 .

[197] Ho HN, Le HH, Le TG, Duong THA, Ngo VQT, Dang CT, et al. Formulation and characterization of hydroxyethyl cellulose-based gel containing metronidazole-loaded solid lipid nanoparticles for buccal mucosal drug delivery. Int J Biol Macromol 2022;194:1010–8. https://doi.org/10.1016/J.IJBIOMAC.2021.11.161 .

[198] Sharifalhoseini M, Es-haghi A, Vaezi G, Shajiee H. Biosynthesis and characterisation of solid lipid nanoparticles and investigation of toxicity against breast cancer cell line. IET Nanobiotechnol 2021;15:654–63. https://doi.org/10.1049/NBT2.12062 .

[199] Yang F, Hu S, Sheng X, Liu Y. Naringenin loaded multifunctional nanoparticles to enhance the chemotherapeutic efficacy in hepatic fibrosis. Biomed Microdevices 2020;22. https://doi.org/10.1007/S10544-020-00524-1 .

[200] Chae J, Kang SH, Kim J, Choi Y, Kang SH, Choi J. Targeted and efficient delivery of rifampicin to macrophages involved in non-tuberculous mycobacterial infection via mannosylated solid lipid nanoparticles. Nanoscale Adv 2023;5:4536–45. https://doi.org/10.1039/D3NA00320E .

[201] Ramalingam P, Ganesan P, Prabakaran DS, Gupta PK, Jonnalagadda S, Govindarajan K, et al. Lipid Nanoparticles Improve the Uptake of α-Asarone Into the Brain Parenchyma: Formulation, Characterization, In Vivo Pharmacokinetics, and Brain Delivery. AAPS PharmSciTech 2020;21. https://doi.org/10.1208/S12249-020-01832-8 .

[202] Farsani PA, Mahjub R, Mohammadi M, Oliaei SS, Mahboobian MM. Development of Perphenazine-Loaded Solid Lipid Nanoparticles: Statistical Optimization and Cytotoxicity Studies. Biomed Res Int 2021;2021. https://doi.org/10.1155/2021/6619195 .

[203] Chaudhuri A, Naveen Kumar D, Kumar D, Kumar Agrawal A. Functionalized solid lipid nanoparticles combining docetaxel and erlotinib synergize the anticancer efficacy against triple-negative breast cancer. Eur J Pharm Biopharm 2024;201. https://doi.org/10.1016/J.EJPB.2024.114386 .

[204] Rahdari T, Mahdavimehr M, Ghafouri H, Ramezanpour S, Ehtesham S, Asghari SM. Advancing triple-negative breast cancer treatment through peptide decorated solid lipid nanoparticles for paclitaxel delivery. Sci Rep 2025;15:6043. https://doi.org/10.1038/S41598-025-90107-Y .

[205] Rath PP, Makkar H, Agarwalla SV, Sriram G, Rosa V. Stearic acid nanoparticles increase acyclovir absorption by oral epithelial cells. Dent Mater 2024;40. https://doi.org/10.1016/J.DENTAL.2024.07.005 .

[206] Huang R, Zhu Y, Lin L, Song S, Cheng L, Zhu R. Solid Lipid Nanoparticles Enhanced the Neuroprotective Role of Curcumin against Epilepsy through Activation of Bcl-2 Family and P38 MAPK Pathways. ACS Chem Neurosci 2020;11:1985–95. https://doi.org/10.1021/ACSCHEMNEURO.0C00242 .

[207] Anantaworasakul P, Chaiyana W, Michniak-Kohn BB, Rungseevijitprapa W, Ampasavate C. Enhanced Transdermal Delivery of Concentrated Capsaicin from Chili Extract-Loaded Lipid Nanoparticles with Reduced Skin Irritation. Pharmaceutics 2020;12. https://doi.org/10.3390/PHARMACEUTICS12050463 .

[208] Ahmed MM, Fatima F, Anwer MK, Aldawsari MF, Alsaidan YSM, Alfaiz SA, et al. Development and characterization of Brigatinib loaded solid lipid nanoparticles: In-vitro cytotoxicity against human carcinoma A549 lung cell lines. Chem Phys Lipids 2020;233. https://doi.org/10.1016/J.CHEMPHYSLIP.2020.105003 .

[209] Mokhtar HI, Khodeer DM, Alzahrani S, Qushawy M, Alshaman R, Elsherbiny NM, et al. Formulation and characterization of cholesterol-based nanoparticles of gabapentin protecting from retinal injury. Front Chem 2024;12. https://doi.org/10.3389/FCHEM.2024.1449380 .

[210] Zhang F, Liu Z, He X, Li Z, Shi B, Cai F. β-Sitosterol-loaded solid lipid nanoparticles ameliorate complete Freund's adjuvant-induced arthritis in rats: involvement of NF-κB and HO-1/Nrf-2

pathway. Drug Deliv 2020;27:1329–41. https://doi.org/10.1080/10717544.2020.1818883 .

[211] Yassemi A, Kashanian S, Zhaleh H. Folic acid receptor-targeted solid lipid nanoparticles to enhance cytotoxicity of letrozole through induction of caspase-3 dependent-apoptosis for breast cancer treatment. Pharm Dev Technol 2020;25:397–407. https://doi.org/10.1080/10837450.2019.1703739 .

[212] Raghunath I, Koland M, Sarathchandran C, Saoji S, Rarokar N. Design and optimization of chitosan-coated solid lipid nanoparticles containing insulin for improved intestinal permeability using piperine. Int J Biol Macromol 2024;280. https://doi.org/10.1016/J.IJBIOMAC.2024.135849 .

[213] Sharma M, Chaudhary D. In vitro and in vivo implications of rationally designed bromelain laden core-shell hybrid solid lipid nanoparticles for oral administration in thrombosis management. Nanomedicine 2022;42. https://doi.org/10.1016/J.NANO.2022.102543 .

[214] Huang R, Zhu Y, Lin L, Song S, Cheng L, Zhu R. Solid Lipid Nanoparticles Enhanced the Neuroprotective Role of Curcumin against Epilepsy through Activation of Bcl-2 Family and P38 MAPK Pathways. ACS Chem Neurosci 2020;11:1985–95. https://doi.org/10.1021/ACSCHEMNEURO.0C00242 .

[215] Fahimnia F, Nemattalab M, Hesari Z. Development and characterization of a topical gel, containing lavender (Lavandula angustifolia) oil loaded solid lipid nanoparticles. BMC Complement Med Ther 2024;24. https://doi.org/10.1186/S12906-024-04440-2 .

[216] Alam P, Ezzeldin E, Iqbal M, Mostafa GAE, Anwer MK, Alqarni MH, et al. Determination of Delafloxacin in Pharmaceutical Formulations Using a Green RP-HPTLC and NP-HPTLC Methods: A Comparative Study. Antibiotics (Basel) 2020;9. https://doi.org/10.3390/ANTIBIOTICS9060359 .

[217] Diwan R, Ravi PR, Pathare NS, Aggarwal V. Pharmacodynamic, pharmacokinetic and physical characterization of cilnidipine loaded solid lipid nanoparticles for oral delivery optimized using the principles of design of experiments. Colloids Surf B Biointerfaces 2020;193. https://doi.org/10.1016/J.COLSURFB.2020.111073 .

[218] Zhao E, Yi T, Du J, Wang J, Cong S, Liu Y. Experimental Study on the Resistance of Synthetic Penicillin Solid Lipid Nanoparticles to Clinically Resistant Staphylococcus aureus. Comput Math Methods Med 2021;2021. https://doi.org/10.1155/2021/9571286 .

[219] Rahdari T, Mahdavimehr M, Ghafouri H, Ramezanpour S, Ehtesham S, Asghari SM. Advancing triple-negative breast cancer treatment through peptide decorated solid lipid nanoparticles for paclitaxel delivery. Sci Rep 2025;15:6043. https://doi.org/10.1038/S41598-025-90107-Y .

[220] Calienni MN, Scavone MA, Sanguinetti AP, Corleto M, Di Meglio MR, Raies P, et al. Lipid Nanoparticle Formulations for the Skin Delivery of Cannabidiol. Pharmaceutics 2024;16. https://doi.org/10.3390/PHARMACEUTICS16121490 .

[221] Penugonda S, Beesappagari P, Repollu M, Badiginchala P, Qudsiya S, Mala CUS, et al. Enhanced Anticancer Efficiency of Curcumin Co-Loaded Lawsone Solid Lipid Nanoparticles Against MCF-7 Breast Cancer Cell Lines: Optimization by Statistical JMP Software-Based Experimental Approach. Assay Drug Dev Technol 2025. https://doi.org/10.1089/ADT.2024.125 .

[222] Chin B, Meng Lim W, Almurisi SH, Madheswaran T. A quality-by-design approach to develop abemaciclib solid lipid nanoparticles for targeting breast cancer cell lines. Ther Deliv 2025;16. https://doi.org/10.1080/20415990.2025.2457314 .

[223] Sinha S, Ravi PR, Somvanshi M, Rashmi SR. Solid lipid nanoparticles for increased oral bioavailability of acalabrutinib in chronic lymphocytic leukaemia. Discover Nano 2024;19. https://doi.org/10.1186/S11671-024-04157-8 .

[224] Naidu ECS, Olojede SO, Lawal SK, Peter AI, Akang EA, Azu OO. Effects of vancomycin linoleic acid nanoparticles on male reproductive indices of Sprague-Dawley rats. Artif Cells Nanomed Biotechnol 2021;49:587–95. https://doi.org/10.1080/21691401.2021.1968883 .