Original Research Article

Development and Physicochemical Characterization of Solid Lipid Nanoparticles Containing Allopurinol

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ABSTRACT

Gout is a painful inflammatory condition caused by the accumulation of urate crystals in joints, typically resulting from elevated blood uric acid levels. Allopurinol is commonly used for long-term treatment and prevention of gout. However, its clinical efficacy is limited by poor solubility and bioavailability. This study aimed to develop and characterize solid lipid nanoparticles (SLNs) containing allopurinol (ALP-SLNs) to overcome these limitations. ALP-SLNs were prepared using the emulsification and low-temperature solidification method, employing Glycerol Monostearate (GMS) as the lipid matrix and Poloxamer 188 as the surfactant. Formulation and process parameters were optimized using Design Expert software. The physicochemical properties of the nanoparticles were evaluated, including particle size (PS), polydispersity index (PDI), zeta potential, and drug encapsulation efficiency (EE). The optimized formulation exhibited a particle size of 145.1 nm, a PDI of 0.212, a zeta potential of –21.70 mV, and an encapsulation efficiency of 97.33%. These results indicate successful fabrication of ALP-SLNs with desirable characteristics for enhancing allopurinol delivery.

Introduction

An attack of gout is marked by excruciating pain and swelling due to the accumulation of urate crystals in the joint. Urinary crystals may occur if your blood uric acid level is elevated [1].

Gout is treated and prevented over the long run using allopurinol. When taken consistently, it can reduce gout attacks and help shield your joints from harm. High blood urate levels can cause gout in certain individuals. The body naturally manufactures urate every day. Normally, this dissolves in your blood and exits your body primarily through urination. On the other hand, urate crystals may accumulate in and around your joints if your body produces too much urate or is unable to adequately eliminate it. You may not be aware that these crystals are steadily forming for years. After the formation of many crystals, they may shed into the joint, resulting in excruciating inflammation. The way allopurinol functions is by reducing the level of urate in your blood. This is why it is occasionally referred to as urate lowering therapy (ULT). Your urate level will eventually drop to the point where no more crystals can form and those that already exist will gradually dissolve [2]. Recent years have seen a significant increase in interest in Solid Lipid (SLN) Nanotechnology because of its many advantages for the pharmaceutical industry. Nanosized medication molecules increase absorption and enhance therapeutic effectiveness when compared to conventional

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drug molecules. Furthermore, the pharmaceutical industry has embraced nanotechnology as a key instrument for investigating and creating novel drug delivery methods, including targeted treatment, sustained release, and localized drug administration. With the goal of lowering medication administration frequency, boosting treatment adherence, and raising patient quality of life, these developments seek to address the drawbacks of traditional medications and formulations, including limited solubility, poor bioavailability, and widespread dispersion [3,4].

Solid lipid nanoparticles (SLNs) are one of these strategies that stand out as a potentially useful paths. SLNs are lipid-based nanoparticles that are distributed in water or aqueous surfactant solutions while in a solid form at room temperature. The excellent biocompatibility of solid lipid nanoparticles (SLNs) is one of their many remarkable advantages. Less toxicity, greater cellular penetration, better medication solubility, a lower chance of allergic responses, and improved drug solubility are other benefits. BCS Class II and IV drugs are best delivered by SLN due to their special properties and characteristics [3-7].

Allopurinol

Allopurinol (Figure 1) comes under BCS Class IV drugs, which means allopurinol has low solubility and low permeability [5]. Formulating the SLNs containing allopurinol and assessing some of theformulations' physicochemical characteristics were the goals of this investigation. A xanthine oxidase inhibitor called allopurinol, which lowers urates, has been licensed by the FDA to treat gout, prevent TL syndrome (tumor lysis syndrome), and prevent recurring calcium nephrolithiasis in people with

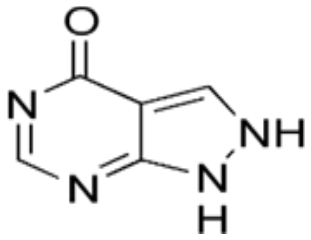


Figure 1: Chemical structure of Allopurinol

hyperuricosuria [6]. Allopurinol is a medication used to reduce urate levels because it inhibits xanthine oxidase.

The FDA has approved allopurinol for the following purposes:

1. Gout,
2. Use in prevention from TL syndrome, and
3.Preventing individuals with hyperuricosuriafrom developing recurrent calcium nephrolithiasis.

Furthermore, the prevention of recurrent uric acid nephrolithiasis and hyperuricemia linked to Lesch-Nyhan syndrome is a non-FDA-approved indication [2,7].

In the following circumstances, the American College of Rheumatology advises starting urate-lowering medication, such as allopurinol, in patients who have a confirmed diagnosis of gouty arthritis:

1. Acute gouty arthritis strikes occurs often, defined as two or more episodes annually.
2. Stage 2 chronic renal disease or higher,
3. Tophi or tophus detected during a clinical examination or imaging, and
4. History of nephrolithiasis

Results and Discussion

Selection of Solid Lipids And Surfactant

Due to the solid lipid's self-emulsifying property, which will further help to enhance the allopurinol's bioavailability at the necessary site and increase its oral bioavailability, the highest solubility of allopurinol was obtained in the GMS (Glycerol monostearate) (93.52 ± 0.89 mg/100 mg), as indicated in Table 1 [8]. In contrast, Poloxamer provided the GMS and

allopurinol compatibility between the surfactant scenario, as seen in Figure 2. Poloxamer 188 is a non-ionic surfactant that is safe for human use since it has minimal toxicity hazards [9].

Table 1: Screening of lipid via solubility

Lipids	Solubility mg/mg	Percentage solubility in Lipid
Steric acid	2.05 mg/1mg (drug)	92.92 ± 0.67%
GMS	1.60 mg/1mg (drug)	93.52 ± 0.89%

FTIR compatibility study

The FTIR spectrum of allopurinol exhibited characteristic peaks, as shown in Figure 2 Table 2 indicates a comparison between the components of allopurinol-SLN IR spectra and the IR spectra of pure allopurinol API [10].

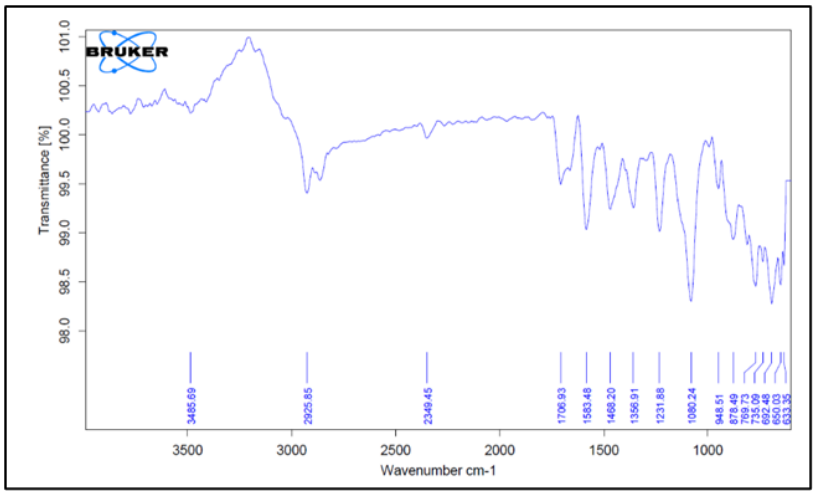


Figure 2: IR spectrum of SLN composition with allopurinol

Based on Table 2, it is evident that the allopurinol molecule is compatible with the excipients used during the development of ALP-SLNs, indicating no drug-excipient interaction occurred during development. Therefore, the formulation is expected to have no- toxic effect after consumption. There are no shown any kind changes in the respective peak of allopurinol [11].

Table 2: Interpretation of SLN composition with allopurinol

Sr. No	Functional Group	Observed Peak (cm-1) Standard API	API + Excipient
1	C=N & C=O (Stretch)	1,698.43	1,706
2	N-H Bend	1,577.57	1,583
3	C-C (Stretch)	1,469	1,468
4	C-N Stretch	1,354.54, 1,226, and 1,069	1,356, 1,231, and 1,080
5	O-H Bend	1,150.37	1,148
6	C-H	1,354 and 697	1,356 and 692

Formulation Composition Optimization

Nine runs were produced when independent and dependent elements were added to the CCRD design, and several formulations were created based on the results of these runs. For PS and EE, these prepared assertions were being assessed. Table 2 presents these factors.

Response Surface Exploration

Effect Of Independent Factors

Particle size: It was discovered that the values of the developed ALP-SLNs' measured PS fell between 254.4 and 145.1 nm. The concentration of the solid lipids and surfactants, duration had a significantly significant ($p < 0.0001$) influence on the PS values, according to the quadratic equation that was thus generated. It is likely that an increase in the quantity of solid lipids will cause the particle size of the formulation to grow. The particle size of the formulation will probably rise with an increase in the amount of solid lipids [11]. In contrast, when the quantity of surfactant increases, there is a decrease in the interfacial surface tension between the hydrophilic and lipidic sections, resulting in a drop in PS [11]. Figure 3(a) shows the effect of these independent factors in combination with the PS. The combinations of solid lipids and surfactants had a negative outcome. Lipid concentration also had a detrimental effect on PS. However, the quantity of surfactant had a favorable effect on the PS.

$$\text{Particle size} = 159.77 + 6.93(X1) - 16.95(X2) - 1.62(X1)\,(X2) + 59.70(X1)2 + 7.75(X2)2$$

Entrapment efficiency: All of the acquired runs' EEs were determined to fall between 92.48 and 98.91%. There was a rise and fall in the EE as a result of the independent levels' highly significant effects on the EE of allopurinol in SLNs ($p < 0.0001$). Based on the linear polynomial equation that was created, the rise in solid lipid led to an increase in the EE because the medications were entrapped in considerable amounts [16]. Furthermore, a rise in surfactant quantity led to an increase in allopurinol's EE due to the formation of the particle's many surfactant layers. Moreover, there's a strong likelihood that poloxamer will increase the medication's solubility. The combined influence of the individual parameters on the EE is also displayed in Figure 3(B). Due to the significant allopurinol entrapment, the combination of surfactant and solid lipid content is beneficial for EE [13].

$$\%\ \text{Drug Entrapment Efficiency (R2)} = 96.20 + 1.76(X1) + 1.32(X2)$$

Design validation: To achieve the best PS and EE, the CCRD was employed in the preparation process. The design validation consists of anticipated values for every response and component. Consequently, allopurinol-SLNs were created using the run and process factors, as well as the responses. It was also observed that there was similarity between the expected and experimental results, indicating the soundness of the optimization process.

Optimized Formula for the Development of ALP-SLN

The optimized ALP-SLNs were made using a 2% w/v solid lipid mixture and 0.67% w/v surfactant concentration after CCRD was applied. Allopurinol was mixed with the lipidic phase and then chloroform was used to encapsulate the drug. Following the aqueous phase's development, the lipid phase was added. After that, it was homogenized for two hours at 4,000 rpm to produce ALP-SLNs. This formulated creation was then given many unique features [14].

Result and Discussion

Characterization of Drug and Allopurinol SLN

Drug

Organoleptic Properties

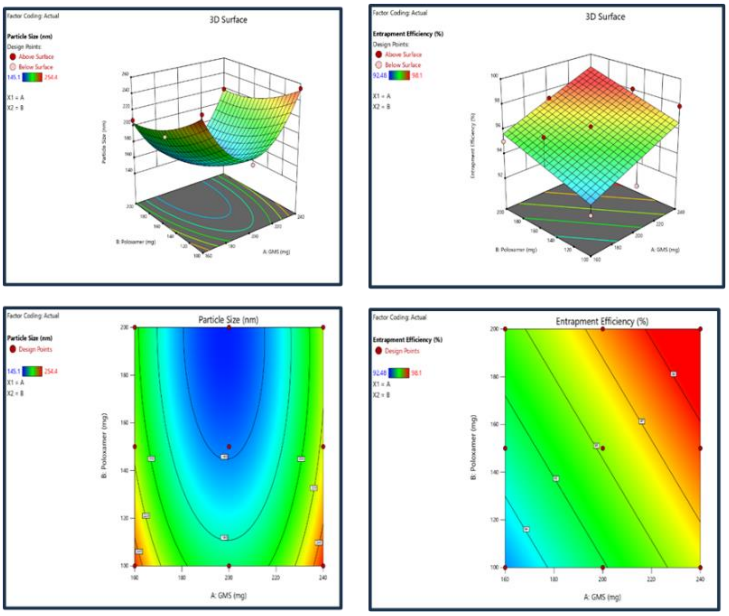
Allopurinol was checked for its colour, odour and taste. Allopurinol is off white amorphous powder in appearance, odourless and bitter in taste.

Identification of Drug (Allopurinol)

a. Fourier Transform Infra-Red spectroscopy

The FTIR analysis of allopurinol was performed and the characteristic peaks of Allopurinol shown in spectrum. Here the interpretation of allopurinol is presented in Table 3.

Allopurinol's infrared spectra show many prominent peaks that are indicative of distinct molecular lengths and functional groups (Figure 4). The stretching vibrations of carbon-nitrogen (C=N) and carbon-oxygen (C=O) double bonds are represented by the peak at 1,698.43 cm^{-1}, which is most likely connected to the imidazole ring and ketone group in allopurinol. The amino group connected to pyrazole ring is responsible for N-H bending vibrations, which correspond to the peak at 1,577.57 cm^{-1}. The carbon-carbon bonds within the molecule's ring structure are reflected by the C-C stretching vibrations, which are detected at 1,469 cm^{-1}. Due to the imidazole ring and other nitrogen-containing functional groups, the peaks at 1,354.54, 1,226, and 1,069 cm^{-1} are associated with C-N stretching vibrations. The signal at 1,150.37 cm^{-1} indicates an O-H bending vibration, which is probably caused by any hydroxyl groups in the molecule. The C-H stretching vibrations represented by the peaks at 1,354 and 697 cm^{-1} are finally related to the hydrogen atoms that are bonded to the carbon atoms in the imidazole ring of allopurinol [19-21].



(A) **(B)**

Figure 3: Effect of variable on A) particle size B) entrapment efficiency

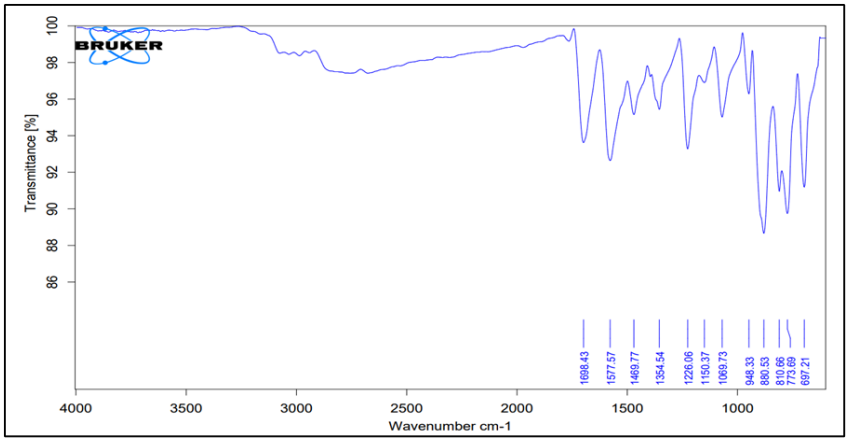


Figure 4: IR spectrum of standard API

b. By UV Spectroscopy According to Pharmacopeia

The test results indicate the maximum absorption at 250.20 nm and the minimum absorption at 229.60 nm (Figure 5), which are in accordance with the standard readings listed in reference books such as the Pharmacopeias (standard values at 250 nm and 231 nm) [22].

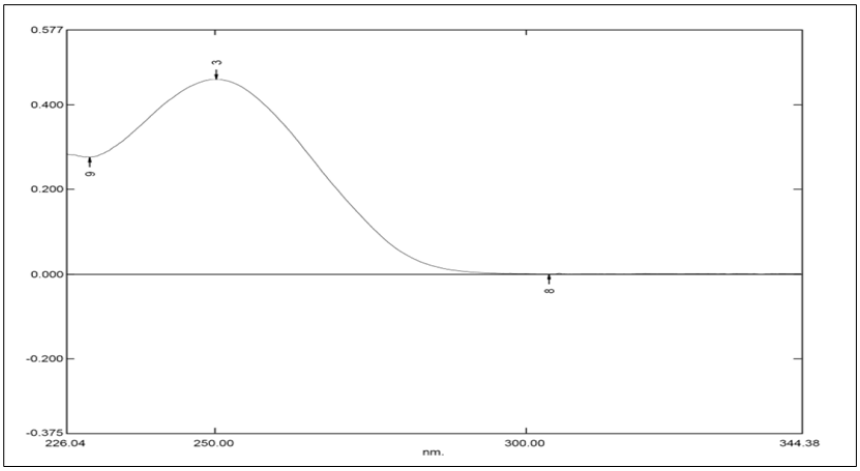


Figure 5: UV spectroscopy represents the maximum and minimum absorption

Table 3: Maximum and minimum absorption of drug in UV spectroscopy

Sr. No.	Intensity	Absorption	Wavelength
1	Maximum	0.651	250.20 nm
2	Minimum	0.420	290.60 nm

Melting point determination: (IP 2018)

The Capillary Rise Method was used to determine the allopurinol's melting point. Below is an illustration of the outcome [22].

Table 4: Melting Point

Sr. No.	Melting point Range	Standard Value	Result
1	348-352 ℃	350 ℃	Complies

Formulation Characterization

PS and PDI: As demonstrated in Figure 6, the improved ALP-SLN formulation the particle size of 145.1 nm and PDI of 0.212. These parameters collectively indicate a well-optimized nanoparticulate system. They support the development, scalability, and therapeutic performance of the formulation, making it a strong candidate for further pharmaceutical advancement. Hence, the PS derived from SLN loaded with allopurinol is most suited for the formulation's development [15]. Therefore, releasing allopurinol at the appropriate location may eventually alleviate gout and help prevent tumor lysis syndrome [16]. Additionally, the generated formulation's PDI was found to be below the range of 0.0 to 1.0, specifically 0.212, indicating that it was stable and uniform and devoid of any type of aggregation [17,18]. The PS and PDI of the other batches are provided in Table 6.

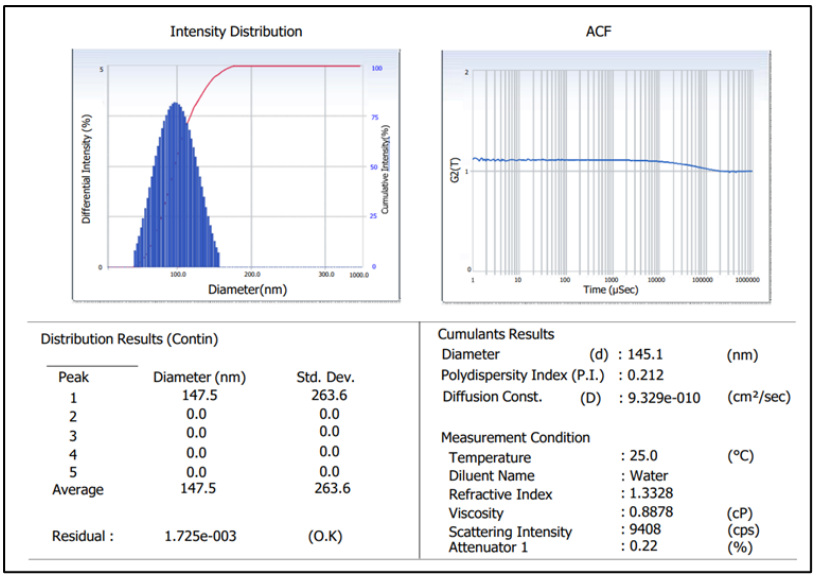


Figure 6: Particle size and PDI of optimized batch of allopurinol SLN

Table 5: Result of PS and PDI of each batch of SLN suggested by software

Sr. No.	Batch Code	Particle Size(nm)	PDI
1	AF 1	236.9	0.227
2	AF 2	208.7	0.223
3	AF 3	207.5	0.231
4	AF 4	181.5	0.223
5	AF 5	168.2	0.249
6	AF 6	145.1	0.212
7	AF 7	254.4	0.242
8	AF 8	221.8	0.242
9	AF 9	218.5	0.231

% Entrapment Efficiency

It was discovered that formulation (AF9) had the maximum entrapment efficiency (98.91%), whereas formulation (AF1) had the lowest entrapment efficiency (92.48%). Table 7 indicates that the changes in the concentrations of surfactants and lipids were suggested as the cause of the variation in entrapment efficiency. The findings demonstrate that the drug entrapment efficiency rose with increases in lipid and surfactant concentrations [18]. EE of optimized batch of allopurinol-SLNs was obtained to be 98.91 %, indicating that the solid lipids and surfactants used in the formulation development were able to capture this quantity of allopurinol [19].

Zeta Potential

Zeta potential, which denotes formulation stability, was measured in the range of -8 to -23 [20]. Malvern Zeta-Sizer was used to assess the zeta potential. The outcome is displayed in Table 7. As shown in Figure 7, the zeta potential of the created formulation Allopurinol-SLNs is observed to be -21.70 mV. It is evident that the resulting value is extremely close to -30 mV, since this ZP value falls within the range of -30 mV to 30 mV. This suggests that the produced formulation is very close to stability. This ZP result further indicates that there is no aggregation in the improved formulation [31].

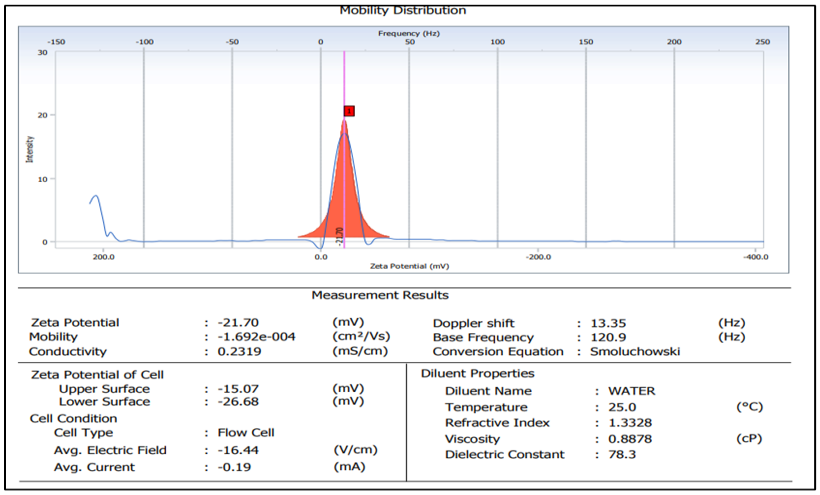


Figure 7: Zeta potential of optimized batch of allopurinol SLN

Drug Loading

The percentage of drug loading was calculated as follows:

$$\% \text{ Drug Loading} = \frac{Weight\ of\ Drug\ In\ SLN}{Weight\ of\ total\ amount\ of\ lipid,emulsifier\ and\ drug\ add} \times 100$$

Table 7 indicates the % drug loading of the developed SLNs (AF1-AF9). The formulation (AF1) with the maximum drug loading, at 25.68%, was determined to have the lowest drug content, at 18.32% (AF9). Reduced possible side effects from overdosing materials and lower production costs of nanomedicine are two benefits of high drug-loading SLNs, minimal quantity of nanoparticles required to reach the therapeutic level [21]. Therefore, a high drug-loading nanoparticles would be ideal for obtaining the high drug dosage with less carrier material.

Table 6 : Result of drug etrapmrnt, zeta potential, and drug loading of fomulation(n = 3, mean ± s.da)
(n = 3, mean ± s.da)

Sr. No.	Batch Code	%EE	%Drug Loading	Zeta Potential
1	AF 1	92.48 ± 1.45%	25.68 ±1.05 %	-10.60
2	AF 2	96.78 ± 1.76%	22.97 ±1.23 %	-11.95
3	AF 3	95.04 ± 1.22%	20.66 ± 1.45%	-12.40
4	AF 4	93.00 ± 1.56%	23.25 ± 1.33%	-13.46
5	AF 5	96.25 ± 1.78%	21.38 ± 1.59%	-23.27
6	AF 6	97.33 ± 1.66%	19.46 ± 1.26%	-21.70
7	AF 7	97.87 ± 1.56%	22.24 ± 1.36%	-12.20
8	AF 8	98.10 ± 1.22%	20.02 ± 1.52%	-8.65
9	AF 9	98.91 ± 1.01%	18.32 ± 1.45%	-10.34

a Standard deviation.

Materials and Methods

Materials

Allopurinol was obtained from Indoco Remedies Ltd., Patalganga (India), Steric Acid was purchased from Laboratory Reagent,

Glycerol Monostearate (GMS) was purchased Chemdyes Corporation, Poloxamer 188 was purchased from Yarrow pharma, Chloroform was purchased from Simson.

Methods

Selection of Solid Lipid and Surfactant

Allopurinol's solubility was examined in a variety of lipid solutions, including stearic acid and GMS [22]. For ten minutes, an excess of medication was combined with a known amount of melted lipids. The medication was dissolved in lipid using a bath sonicator. The medication is dissolved, and any remaining drug is washed away with water in the lipid wash. After that, the lipid was melted, and 1 milliliter of the melted lipid was diluted to make 10 milliliters in 0.1 NaOH. Subsequently, the contents were centrifuged at 5,000 rpm for 30 minutes. Aliquots of supernatant-saturated solvent systems were UV spectrophotometrically analyzed after being appropriately diluted with the appropriate solvent [23].

Compatibility Study of Drug and SLN Compositions

Fourier Transform Infrared Spectroscopy: The compatibility between allopurinol, GMS and Poloxamer 188 used was examined using FTIR spectroscopy. The absorbance band positions and shapes are examined in great detail using the FTIR spectroscopy technique.

This analysis compares the positions and structures of functional groups in the investigated excipients and active component [24,25]. The disappearance of an absorption peak, peak intensity reduction, or the appearance of additional peaks will all indicate the presence of interactions between allopurinol, the API, and the excipients being studied GMS and Poloxamer 188.

Preparation of Allopurinol-Loaded Solid Lipid Nanoparticles (SLN) using the Emulsification and Low-Temperature Solidification method**:**

1. Preparation of Organic Phase: The required amount of allopurinol was dissolved in 0.1 N NaOH solution. Glyceryl monostearate (GMS) was dissolved in 10 mL of chloroform at a temperature above 50 °C.

2. Preparation of Aqueous Phase: Poloxamer 188 was dissolved in 30 mL of distilled water at 75 °C.

3. Emulsification: The allopurinol solution was added to the aqueous phase under continuous stirring. The organic phase was gradually introduced into the aqueous phase using a syringe, while stirring continuously.

4. Stirring and Solvent Evaporation: The mixture was stirred at 1,000 rpm for 1 hour until the organic solvent completely evaporated. The system volume was reduced to approximately 5 mL.

5. Solidification: The condensed system was rapidly cooled to a temperature between 0 and 4 °C. 10 mL of cold distilled water was added, and the mixture was homogenized at 4,000 rpm for 2 hours.

6. Separation of Nanoparticles: The resulting suspension was centrifuged at 5,000 rpm for 20 minutes to collect the nanoparticles. The supernatant was discarded, and the precipitate was resuspended in distilled water.

7. Drying and Final Product: The resuspended nanoparticles were further separated and dried using an appropriate technique such as spray drying or lyophilization (freeze-drying) [26,27].

Optimization of Allopurinol Loaded- SLNs

Design Expert (Version 13.0, State-Ease Inc. Minneapolis, USA) was the program used to optimize SLNs. The formulation optimization process made use of one of the frequently utilized designs, the central composite design for response (CCRD) [28]. The developed formulation is expected to have the necessary PS, low PDI, and high EE. Nine runs were recommended to be generated based on the independent variables included in the CCRD, which were the concentration of solid lipids (1.6 – 2.4% w/v) and surfactant concentration (0.33 – 0.67 % w/v). The influence of the independent factors (as indicated in Table 7) on the dependent factors (PS and EE) was noted. These independent factor values were chosen using the hit and trial approach in addition to the ranges listed in typical pharmacological texts.

Table 7: Layout as per 3^2 Central Composite design

Sr. No.	Batch Code	Variable Level in Coded Form		Depended Variable	
		X1	X2	Particle Size (nm)	% EE
1	AF 1	-1	-1	236.9	92.48
2	AF 2	-1	0	208.7	96.78
3	AF 3	-1	+1	207.5	95.04
4	AF 4	0	-1	181.5	93.00
5	AF 5	0	0	168.2	96.25
6	AF 6	0	+1	145.1	97.33
7	AF 7	+1	-1	254.4	97.87
8	AF 8	+1	0	221.8	98.10
9	AF 9	+1	+1	218.5	98.91

Characterization of Drug and Formulation

Drug

Organoleptic Properties

The drug sample was evaluated for its organoleptic properties such as colour, odour, taste and appearance and the results were recorded.

Identification of Drug

Fourier Transform Infrared Spectroscopy

Using an FTIR spectrophotometer manufactured by Bruker in Germany, the IR spectra of the pure medication allopurinol were acquired and evaluated. The samples were scanned over the wave number range of 4,000-400 cm^{-1}. The interaction of infrared radiation with matter by absorption or reflection is measured. Functional groups in samples were studied [21,22].

Identification of Drug (Allopurinol) by UV Spectroscopy according to Pharmacopeia

10 mg was dissolved in 1 mL of a 0.1 N sodium hydroxide (NaOH) solution, and then diluted to 100.0 mL with a 0.1 N hydrochloric acid (HCl) solution.Afterward, a 0.1 N hydrochloric acid solution was used to dilute 10.0 mL of this solution to 100.0 mL (HCl) [22].

Spectral range: 220-350 nm.
Absorption maximum: at 250 nm.
Absorption minimum: at 231 nm.

Melting Point Determination

The Capillary Tube Method was used to measure the melting point of allopurinol. Allopurinol fine powder was put into a glass capillary tube that had been previously sealed on one end. Using a thermometer, the melting point in Thiele's tube was found [22].

Formulation

Particle Size and PDI

Zetasizer (Malvern Zetasizer, Nano ZS, Ltd., UK) and Malvern software were used to assess these parameters. The particle size was reported by the device using dynamic scattering. To achieve a uniform dispersion, dilution was performed up to ten times with Milli Q water, and the temperature was recorded at 25 ± 2 ℃ at 90°.Zetasizer (Malvern Zetasizer, Nano ZS, Ltd., UK) and Malvern software were used to assess these parameters. The particle size reported was generated by the Panalytical Lab software.

Drug Entrapment Efficiency

SLNs (1 mL) were centrifuged for 10 minutes at 5,000 rpm. Following collection, 0.1 N NaOH was used to dilute the filtrate. The drug content was measured at 250.20 nm using the UV spectrophotometer. The amount of medicine that was entrapped was calculated using the equation [29].

$$\% \text{ Entrapment Efficiency } \frac{\text{Total amount of Drug added} - \text{Unloaded drug}}{Total\ amount\ of\ drug\ added\ in\ SLN} \times 100$$

Zeta Potentials

One of the key components that helps determine stability is zeta potential.
It gauges how strongly charges or electrostatic charges repel or attract one another among particles. Its measurement provides a thorough understanding of the factors that lead to flocculation, aggregation, or dispersion, which may be used to optimize the suspension, emulsion, and dispersion processes. The zeta potential values of the samples prepared for particle size investigation were determined using a folded capillary zeta cell.
This parameter was measured by Zeta-sizer (Malvern Instruments, UK) utilizing the electrophoretic mobility of nanoparticles in an electric field. Once the solution had been diluted with Milli Q water, it was placed inside the chamber [30].

% Drug Loading

SLNs (1 mL) were centrifuged for 10 minutes at 5000 rpm. Following collection, 0.1 N NaOH was used to dilute the filtrate. The drug content was measured at 250.20 nm using the UV spectrophotometer. The calculation was used to determine how much medication was entrapped [31].

$$\% \text{ Drug Loading} = \frac{Weight\ of\ Drug\ In\ SLN}{Weight\ of\ total\ amount\ of\ lipid,emulsifier\ and\ drug\ add} \times 100$$

Conclusion

The successful development of uniformly sized and stable allopurinol-loaded solid lipid nanoparticles (SLNs) was achieved through the strategic selection and optimal combination of excipients—specifically the lipid and surfactant systems-during the fabrication process. The critical formulation parameters including particle size, zeta potential, and polydispersity index (PDI), drug loading, and entrapment efficiency (EE), were meticulously evaluated to ensure performance and stability. Among the tested batches, AF 6 emerged as the optimized formulation, demonstrating exceptional characteristics: Particle size: 145.1 nm; PDI: 0.212; Entrapment efficiency**:** 97.33%; Drug loading: 19.6%; Zeta potential: –21.70 mV; These values fall well within the desired range, confirming the formulation's homogeneity, stability, and absence of particle aggregation**.** The low PDI and favourable zeta potential further reinforce the robustness of the system, ensuring consistent behaviour and minimal risk of instability. The promising analytical profile of AF 6 positions it as a strong candidate for advanced pharmaceutical applications. These nanoparticles hold significant potential to enhance allopurinol's biocompatibility, improve its bioavailability, and amplify its therapeutic efficacy, paving the way for more effective and patient-friendly drug delivery systems.

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Competing interests

The authors declared no conflict of interest.

Authors' Contributions

Concept: S.A. and A.A.; design: S.A. and S.F..; supervision: A.A.; resources: G.J. and A.A.; materials: G.J. and A.A.; data collection and/or processing: S.A. and S..F.; analysis and/or interpretation: S.A.; literature search: S.A.; writing: S.A.; critical reviews: A.A., S.A., and S.F.

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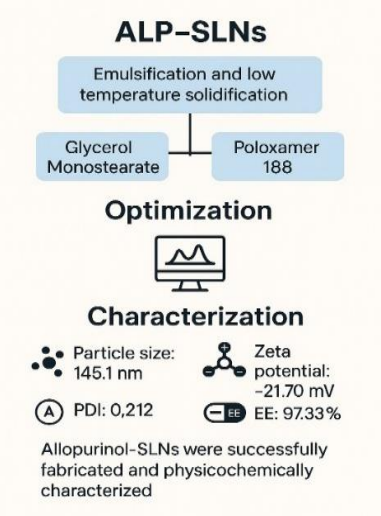
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