

Co-Solvency-Based Solid Dispersion of Ibuprofen Using Tamarind Seed Mucilage: A Sustainable Approach for Solubility and Bioavailability Enhancement

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Abstract:

Ibuprofen is tough to dissolve in water and possess a limited bioavailability. To enhance dissolution, and stability, the study explores co-solvency-based solid dispersion method involving the application of tamarind seed mucilage as a natural polymer carrier. Drug:mucilage ratios of 1:0.5, 1:1, and 1:1.5, employing ethanol as a co-solvent under a solvent evaporation method. Equivalent physical mixtures were prepared for comparison. Along with FTIR and XRD studies endorsing ibuprofen's change to amorphous nature without chemical interaction with carrier, phytochemical tests established the presence of bioactive chemicals in the mucilage. Substantial progress was demonstrated in in vitro dissolving testing; the SD (3) 1:1.5 formulation had a dissolve efficiency of 91.6% and 99.8% drug release within 60 minutes. Particle size and zeta potential measurements indicated stable surface charges and nanoscale particles, particularly for SD (3). Compared to physical blends and pure ibuprofen, solid dispersions showed improved drug content and release effectiveness throughout the semiannual stability test under 40°C, 75% relative humidity. These results illustrate how tamarind seed mucilage can be utilized in co-solvency-based solid dispersions as an effective and environmentally friendly means of increasing solubility and therapeutic effectiveness of drugs with low aqueous solubility. This approach paves the way for improved drug delivery systems through offering a sustainable, scalable alternative and encouraging more research into natural carriers for drug formulations.

Keywords

Ibuprofen; Solid dispersion; Co-solvency method; Tamarind seed mucilage; Natural polymer; Solubility enhancement; Bioavailability; Amorphous drug form; Solvent evaporation; Drug-polymer ratio; In vitro dissolution; Drug release kinetics; FTIR; XRD; Particle size analysis; Zeta potential; Stability studies; Sustainable drug delivery; Green formulation; Poorly water-soluble drugs

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1. Introduction

1.1 Solid Dispersions

Solubility is important property that determines how effectively drug is absorbed and acts within the body¹. Especially in the case of oral medications that have to dissolve within stomach fluids before they can become effective, hard-to-formulate drugs with slow dissolving and limited bioavailability are typically the result². For hydrophobic drugs, particularly those that fall in Class II and Class IV of the Biopharmaceutical Classification System (BCS), this is a major challenge.³ In response to this, researchers are employing natural and synthetic hydrophilic carriers to increase solubility and improve absorption. The application of polymer-based matrices to enhance the bioavailability of these drugs is increasing, and various methods are under development to overcome this chronic issue in drug discovery⁴.

1.1.1 First-Generation

It employ carriers like sugars or urea to deliver stable products with small crystals that enhance dissolution through surface area increase.⁵ These consist of monotectic systems, which are continuous, discontinuous, substitutional, or interstitial depending on crystal structure or miscibility, and eutectic blends, where the drug and carrier crystallize together.⁶ Their crystal structure can hinder drug release even when they are stable⁷. Okonogi et al. demonstrated, for instance, that dispersions of urea were more effective in enhancing solubility along with dissolution of ofloxacin in comparison with mannitol-based ones⁸.

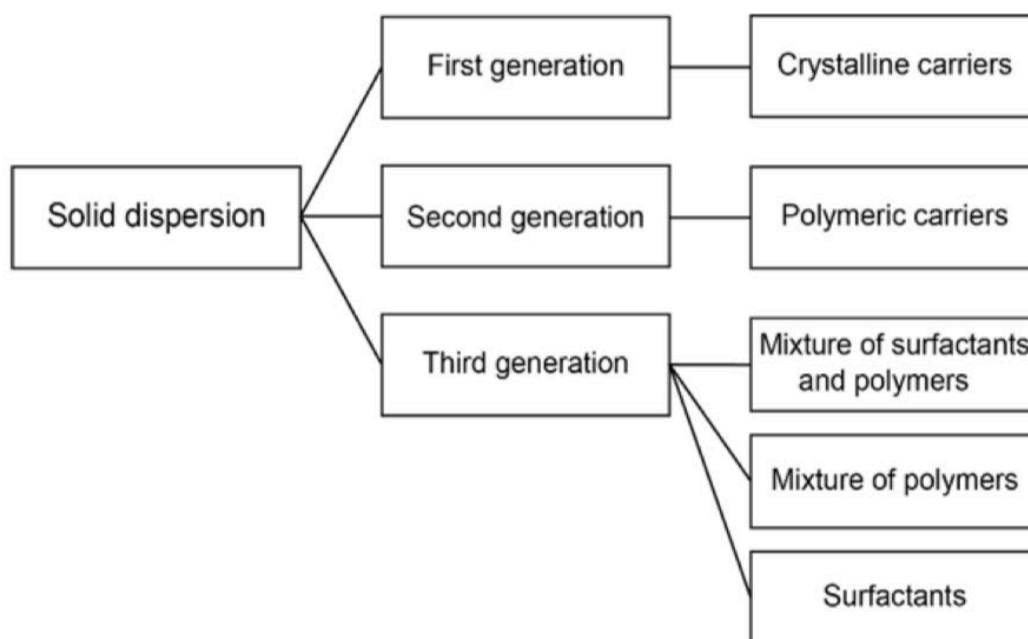


Fig 1.1: Illustrates different generations of solid dispersion.

1.1.2 Second-Generation

They are more rapidly dissolving than crystalline systems due to the utilization of carriers which are amorphous in nature such as cellulose derivatives.⁹ They can form solid solutions where the carrier and drug interact at the molecular level or amorphous solid suspensions with separate drug and carrier phases¹⁰. While issues such as precipitation or phase separation could occur, high molecular weight polymers help to prevent medication recrystallization throughout processing or storage¹¹.

1.1.3 Third- Generation

These dispersions employ carriers like poloxamer, inulin, or Gelucire¹². These enhance chemical and physical stability by alleviating problems like drug crystallization.¹³ The nature and the desired release concentration dictate what carrier to use; high-Tg polymers block recrystallization, while surfactants speed dissolution¹⁴.

1.1.4 Fourth Generation

This system known CRSD, are a compromise between extended release of the drug and enhanced solubility and are ideal for drugs with short half-lives and low water solubility. For delivering tailored release patterns, they employ water-soluble or insoluble polymers like ethyl cellulose, Eudragit types, or HPC.¹⁵

1.2 Drugs Build Up Polymer Matrices

Polymers operate as carriers in solid dispersions, and a stable formulation depends on the drug-polymer interaction.¹⁶ Drug molecules may mix with the polymer's relaxed molecular chains during hot-melt extrusion because heating softens the polymer.¹⁷ Solvents facilitate drug integration by reducing polymer chain interactions in solvent-based techniques such as spray drying.¹⁸ These processes can lead to antiplasticization, where drug hardens polymer, reducing transition temperature of glass (Tg) between two phases, or plasticization, where the polymer becomes softer and its Tg is reduced. Understanding these effects is crucial for maximizing release and ensuring stability of formulation¹⁹.

1.3 Solid-Dispersions Facilitate Drug Release

Solid dispersions make medication release determine oral dose forms' effectiveness, such as tablets or capsules.²⁰ A stable amorphous form and preventing crystallization during supersaturation are prerequisites for consistent absorption. In solid dispersions, medications dissolve quickly to give a burst "spring" effect; precipitation, however, could lead to a lag release.²⁰ In order to avoid this, precipitators are added as precipitation inhibitors by formulators, and these act as a "parachute" to prevent higher concentrations of the drug from precipitating out of solution²¹. Immediate-release dispersions are governed by two main processes: drug-controlled release, which is determined by the drug's properties, and carrier-controlled release, which is governed by the polymer²². For CRSDs, the polymer's solubility and the degree to which it bonds with the drug dictate whether release is through matrix degradation or diffusion²³.

1.4 Carriers function in solid dispersions

These carriers can either be water-attracting (hydrophilic) or water-repelling (hydrophobic), depending upon their ability to dissolve or swell with solvents, resist chemical or thermal degradation, and be safe, inert, and cost-effective²⁴. Carriers fine-tune the performance of a

formulation because, depending on what is sought to be achieved, they will decline the drug release to increase the drug's dissolution.

1.5 Solid Dispersions Assessment

The reason why solid dispersions exist is so that they may enhance bioavailability of sparingly dissolvable aqueous-dissolving medicines.²⁵ To verify their functioning, conventional techniques such as USP dissolution device to assess release rates are used.²⁶ Assessing the drug's even distribution inside the polymer and whether it stays crystalline or amorphous is also crucial.²⁷ Equipment such as visual inspections, spectroscopy, thermal analysis, and microthermal methods may reveal drug-polymer interactions, crystallinity, and the formulation's general stability²⁸.

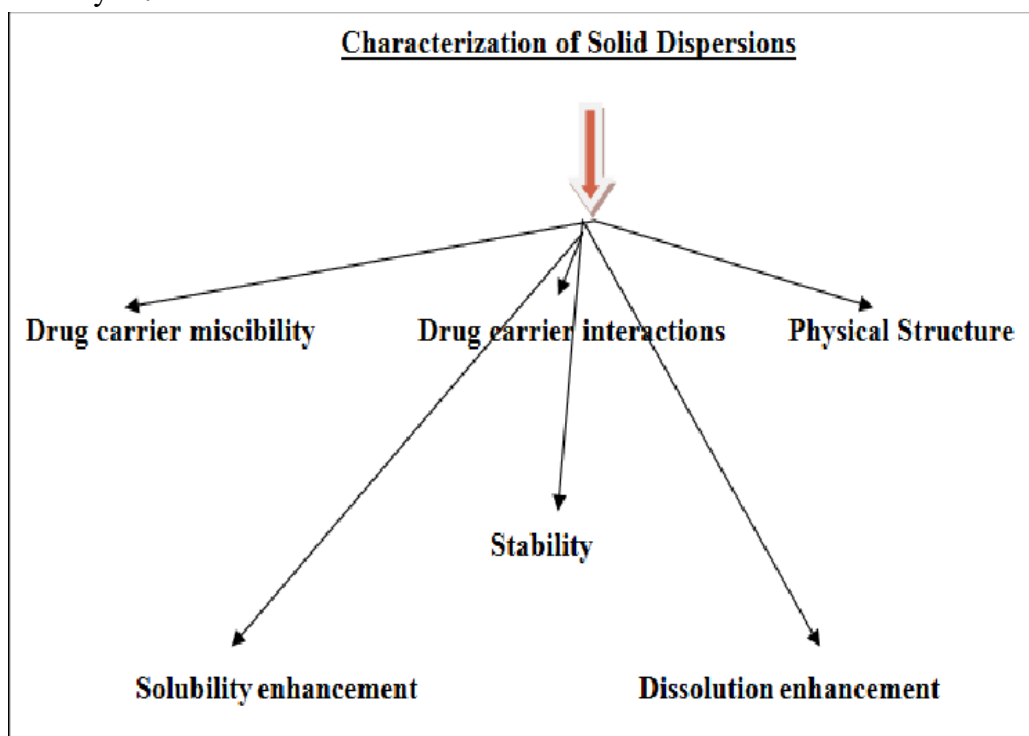


Fig 1.2: characterization of solid dispersion

1.6. Drug Release

1.6.1. Discharge Under the control of the Carrier

According to research by Corrigan (1986), drug release in some dispersions, like PEG, is a function of how fast the polymer dissolves²⁹. This implies a carrier-controlled process where the polymer controls the process. Dubois and Ford (1985), who found that most drugs in the same carrier had the same release rates, corroborated this.³⁰ The drug blocks total drug particles from entering the surrounding fluid directly by molecularly interacting with a polymer-rich surface layer³¹.

1.6.2. Controlled Drug

Sjökvist and Nyström (1991) found that particle size significantly affects the rate of dissolving, which indicates a drug-controlled system³². The drug is administered in smaller particles that break down at a slower rate compared to carrier-controlled systems³³. Improved wetting, reduced clumping, and decreased particle size all facilitate faster dissolution through augmented solubility and increased surface area exposure.³⁴

1.7. Common Methods utilized for Production of Solid Dispersions

All methods followed till date have some advantages and limitations. The common methods for formulating these compounds are mentioned below.

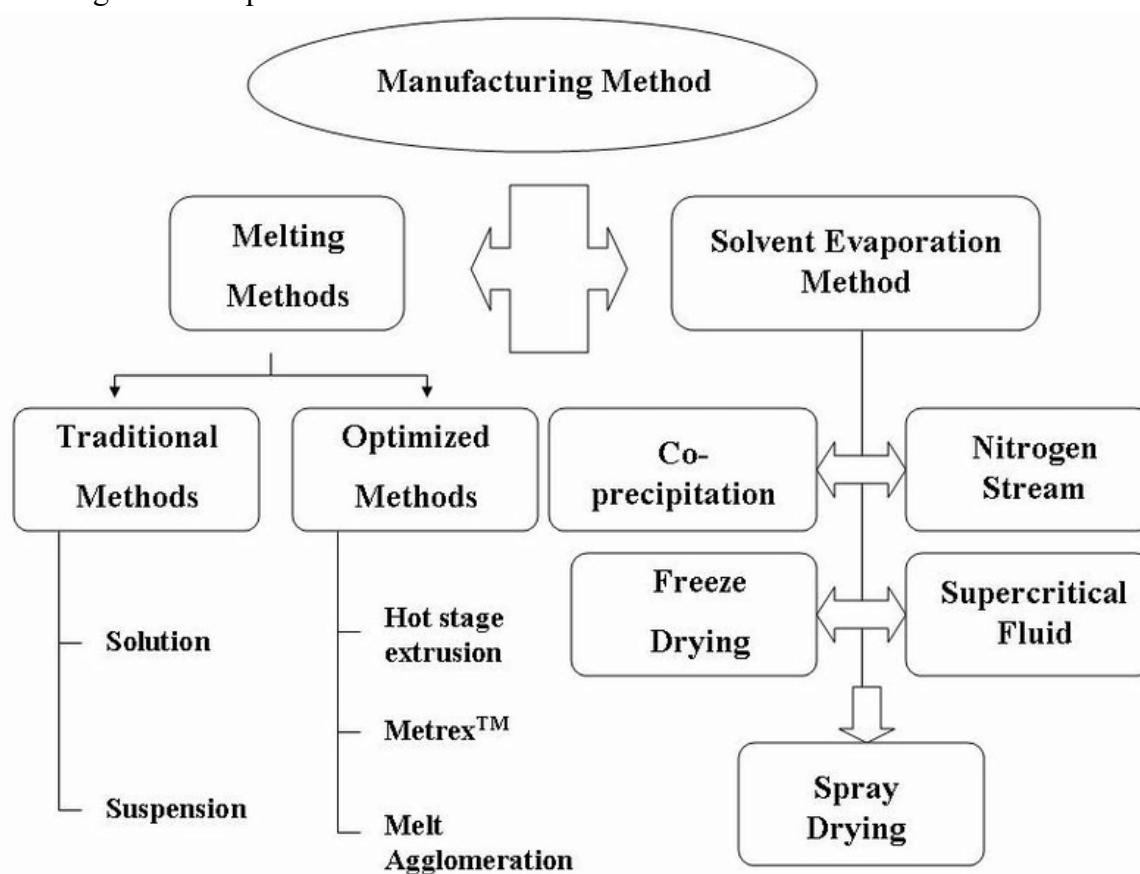


Fig 1.3: Different Manufacturing Process.

1. Fusion

Through this technique, a drug is blended with soluble carrier, and they are melted on heating. Once rapidly cooled in an ice bath or on a cold surface, the liquid melt is crushed and sieved to harden it. Drug molecules are trapped in the carrier matrix by rapid cooling, but volatile ingredients can be lost and heat-sensitive drugs or carriers can be destroyed by heat. These risks can be reduced by processing with inert gases, like nitrogen, or under vacuum ³⁵.

2. Solvent Evaporation

This technique entails dissolution of medication and carrier in same solvent, which further evaporated under strictly controlled conditions resulting solid dispersion. This method does not use high temperatures and yields a dry layer upon completion of solvent evaporation, making it ideal for thermally sensitive products ³⁶.

3. Melt-Solvent

The drug blended with a melting carrier, like PEG, following dissolution in a solvent. A solid drug-loaded matrix is left behind after the evaporation of the solvent. This approach, which has aspects of both solvent and fusion processes, works best for low-dose drugs.

4. Extrusion of Hot Melt

This procedure forms a drug-carrier mixture into forms such as pellets or granules by melting and mixing it with a twin-screw extruder. It is suitable for drugs with low heat sensitivity since due to its short exposure to heat, and its precise control over temperature, feed rate, and screw speed ensures consistent results.

5. The lyophilization process

The carrier and drug are dissolved in a solvent, resulting solution is frozen followed by removal of solvent by vacuum by the process of sublimation. It is suitable for generating molecular systems that are finely divided and is a substitute for solvent evaporation.

6. Agglomeration of Melt

Through melting the medicine and excipients above their melting points, a carrier will act as a molten binder within this method. As a substitute, hot excipients can be sprayed with a hot binder in a high-shear mixer. Final dispersion quality is dependent upon factors such as particle size and binder selection.

7. Surfactant

Surfactants enhance solubilization of medication and wetting, enhancing solid dispersions. They enhance stability and performance by reducing the Tg of carrier, enhancing compatibility, and helping prevent crystallization.

8. Utilization of electrospinning

Technique forms nano- or microfibers by drawing a polymer solution with high-voltage electric fields. Through offering an enormous surface area for rapid breakdown and improved solubility, these fibers consistently trap medications.

9. Supercritical Fluid Technology

Supercritical fluid technology provides an alternative method for enhancing medication solubility, frequently with carbon dioxide (CO₂). Supercritical CO₂, both an antisolvent and a solvent, is sprayed into a chamber filled with a medication. This precipitates the drug into fine particles very rapidly. Heat-sensitive drugs are protected by CO₂'s ease of removal, safety, and capacity to process at near room temperature

10. The Spray Drying Method

A method for making a homogeneous solution in a scalable fashion is spray drying, which means dissolving a carrier and a drug in water. The infinitesimal particles of this solution are collected after it has been atomized within a hot air chamber and sprayed out through a nozzle. Due to evaporation, the powder thus formed can be used with heat-sensitive drugs and must be kept in jars sealed tightly.³⁷

11. Homogenization under High Pressure

Nanosuspensions are created by dispersing drug particles in an aqueous solution containing surfactants and forcing them through a homogenizer at high pressure. Cavitation and mechanical forces reduce particles to the nanoscale range. Hard chemicals can be resistant to size reduction, while softer or fragile drugs respond well. The outcome depends on the material properties, pressure, and homogenization cycles.

1.8. Novelty of Research

This study uses tamarind seed mucilage in a co-solvency-based solid dispersion system to improve the solubility of ibuprofen, a Biopharmaceutical Classification System (BCS) Class II

medication, in a sustainable and novel way. This formulation's twin advantage using a natural, underused polymer as a drug carrier and coupling it with a green co-solvency approach to increase solubility and bioavailability is what makes it innovative. Tamarind seed mucilage has special phytochemical and physicochemical properties biodegradability, biocompatibility, and gelling ability that make it an economical and environmentally beneficial substitute for synthetic polymers, which are often employed for similar applications.

This work presents a straightforward solvent evaporation technique that avoids high temperatures, protecting the integrity of the drug and polymer in contrast to conventional solid dispersions that often experience instability or complicated processing. Additionally, the study thoroughly assesses several drug-to-polymer ratios in order to determine the best formulation that produces the greatest drug release rate, the smallest particle size, and the largest encapsulation efficiency. To verify that ibuprofen was successfully converted to an amorphous state and that it was evenly distributed throughout the polymer matrix. This combination guarantees longer stability under accelerated circumstances in addition to improved solubility.

This research provides a distinctive fusion of conventional plant-based excipients with contemporary pharmaceutical methods, laying the groundwork for future drug delivery systems that put effectiveness, cost, and environmental responsibility first^{38,39}.

2. Literature Review

2.1. Review of Literature

Shaikh et al. (2024) employed guar gum in order to develop dispersions (solid) with the aim of enhancing dissolution of Piroxicam. F1–F5 formulations were developed by varying the drug-to-carrier ratio from 1:1 to 1:5 through the kneading process. FTIR, DSC, SEM, along with solubility and dissolution studies, were employed to analyze these. DSC confirmed that the thermal profile of the drug remained unchanged, and FTIR saw no chemical interaction between Guar Gum and Piroxicam. The 1:5 ratio (F5) exhibited the best performance with a solubility of 0.319 ± 0.02 mg/mL and more than 95% release of the drug within 60 minutes. Higher guar gum concentration improved dissolving by facilitating amorphization, reducing particle agglomeration, and enhancing wettability.

Ajam et al. (2024) employed amorphous solid dispersions (ASDs) to elevate biopharmaceutical & mechanical properties of Ibuprofen, which were subsequently incorporated into sustained-release tablets. Ibuprofen's solubility in various polymer solutions made them select the best polymer, and melt fusion and freeze-drying were employed for their use to form ASDs. The 35 times improvement in solubility achieved by freeze-drying was slightly better than the 28 times improvement obtained through melt fusion. The ASDs doubled in buffer at pH 6.8 because of their increased surface area and amorphous nature. The Weibull model fits best the release kinetics of tablets prepared through direct compression, which give extended drug release over a duration of 12 hours. Ibuprofen solubility, dissolution, and late absorption were significantly improved using this method.

Olagunju et al. (2024) examined natural polymers to improve Ibuprofen's solubility and dissolution using carriers like maize starch, native cassava starch, genetically modified cassava starch, and cassava nanocrystals. The dispersions were characterized by dissolution tests, FTIR, SEM, DSC, and XRD. For optimum solubility enhancement, a 1:2 ratio of starch nanocrystals

was utilized. Ibuprofen's amorphization was confirmed by DSC and XRD, whereas SEM demonstrated increased porosity. The chemical integrity of the drug was demonstrated by FTIR. Substantial dissolution time reductions (T50 of 1.8–4.1 minutes) confirm the efficiency of natural polymers, specifically starch nanocrystals, in enhancing bioavailability.

Kinga et al. (2023) Ibuprofen dispersions with Compritol 888 ATO as plasticizer and Eudragit EPO as the main polymer. Stability and performance of the extrudates, processed at 250 rpm between 90–140°C, were investigated. Component stability was confirmed by thermal testing, chemical bonding to the amorphous system was revealed by FTIR-ATR, and successful amorphization was established by XRPD and DSC. The extrudates remained stable for three months under accelerated storage; the release of Ibuprofen reached its maximum at 140°C and varied between 40% and 63% within 180 minutes. These results validate HME as an effective method for controlled release and solubility of BCS Class II drugs such as, Ibuprofen, where processing conditions play a key role.

O. Shittu et al. (2022) explored the employment of solid dispersions based on a D(-) mannitol and PEG-6000 prepared via the fusion process to enhance ibuprofen solubility and dissolution. They were successful in total incorporation of drug (100%) as well as reasonable yields (96–99%) when examining ratios of drug-to-carrier (1:0:4–1:4:0). Based on dissolution and solubility, all formulations were better than physical blends and raw ibuprofen. The better SD3 formulation (1:2:2) released 50% of the drug in 17 minutes. The amorphous nature of ibuprofen, which enhanced solubility, was evidenced by FTIR and DSC analysis, which don't show chemical interaction. One of the possible ways to elevate oral bioavailability, this modified PEG 6000 and mannitol mixture enhanced wettability and reduced particle clumping.

Marouene et al. (2021) discussed co-milling techniques for ternary ASDs to elevate the solubility and bioavailability drugs like ibuprofen, naproxen, and probucol. In stabilizing the amorphous material and restricting recrystallization, polyvinylpyrrolidone (PVP K30) increased the rate of solubility for ibuprofen and β -cyclodextrin fourfold within ten minutes. The ternary system (ibuprofen, β -cyclodextrin, and PVP at 1:1:0.5) had plasma concentration levels 1.5 to 15 times higher than regular formulations and retained 90% drug release within an hour, which was superior to binary systems. The researchers highlighted the potential for improved therapeutic performance while indicating the necessity of additional rigorous research to understand the processes of stability in such complex systems.

Xiaoning et al. (2021) explored the influence of polymer properties in dissolving in ibuprofen solid dispersions using polymers like PVP, PMOZ, PEOZ, PnPOZ, and PiPOZ prepared by solvent evaporation. Hydrogen bonding and reduced drug crystallinity were confirmed by FTIR, XRD, and DSC. Hydrophilic PMOZ allowed greater crystallization, whereas hydrophobic PVP and PEOZ were better maintained in the amorphous state. PnPOZ performed poorly due to its low critical solution temperature (~25°C), which prevented release despite being theoretically compatible. At dispersion, the semi-crystalline PiPOZ showed structural changes. The results emphasized that performance in solid dispersion is dictated by hydrophobicity, hydrogen bonding, and polymer behavior beyond amorphization.

Ning et al. (2021) fabricated ibuprofen-loaded nanofibers of the core-shell type for rapid dissolution using coaxial electrospinning, a fifth-generation method of solid dispersion. With PVP variations, the shell blended PVP K10 with ibuprofen, while the core contained PVP K90

dissolved in ethanol. The nanofibers were even smooth and an average diameter of 780 ± 120 nm. The amorphous, homogeneously dispersed state of ibuprofen within the polymer, which is maintained by strong intermolecular forces, was confirmed by X-ray diffraction. Ibuprofen was released within one minute, over 20 times faster than with raw drug particles, as observed from in vitro experiments. This new partnership of hydrophilic polymers and nanotechnology offers a very effective technique.

Rongzhen et al. (2021) came up with an innovative method that employs photopolymerization of N-vinyl-2-pyrrolidone (NVP) to develop drug-loaded solid dispersions. This method is a more straightforward technique than the traditional melting or solvent evaporation methods. Fluconazole, ketoconazole, ibuprofen, and artesunate—poorly soluble drugs—were successfully transformed into clear solid dispersions. However, curcumin and resveratrol, being free radical scavengers, inhibited polymerization as revealed by electron spin resonance and UV spectroscopy. Compared to conventional methods, FTIR, DSC, and XRD studies authenticated hydrogen bonding and homogenous molecular distribution in the polymer matrix for ibuprofen and artesunate dispersions, leading to faster and enhanced dissolution.

Neha et al. (2024) employed solid dispersion and hydrotropic methods. They tested hydrotropic agents such as urea and nicotinamide, poloxamers, cyclodextrins, and carriers like, Cyclodextrin, yielded an impressive 67-fold solubility increase, whereas other optimized combinations showed over 35-fold solubility increases. In vitro permeability tests and dissolution confirmed that conversion to amorphous state increased wettability and dispersion, yet cyclodextrin-based dispersions showed comparatively lower permeability. The oral bioavailability of Arteether can be dramatically enhanced using this hydrotropic and polymeric combination.

5.1. Material

Table 5.1: shows the material utilization in the formulation.

S. No.	Material	Source
1	Tamarind Seed	Market
2	Ibuprofen	Sagar Pharmaceuticals
3	Ethanol	Local market
4	Water (Distilled)	Laboratory

5.2. Instruments utilized

Table 5.2: shows the instruments utilized

S.no.	Instruments	Purpose
1	Mortar and pestle	Powdering solidified dispersions
2	30-Mesh Sieve	Sieving solid dispersions
3	Screw-Cap Vial	Storage of solid dispersions
4	Desiccator	Maintaining dry storage conditions

5.3. Formulation

Preparation of Mucilage from Tamarind Seeds

The tamarind seeds were soaked in water to soften and swell them for the purpose of extracting the polysaccharide. They were soaked, and the gel-like, thick mucilage was harvested by filtering them through a muslin cloth. Ethanol was added to this extract to clean it by inducing the precipitation of the polysaccharides. To prepare the final mucilage, which may serve as a natural polymer carrier for subsequent formulations, precipitate was filtered again and left to air dry.⁴⁰

Solid Dispersions Preparation

With ibuprofen as model drug and tamarind seed mucilage as carrier, solid dispersions were prepared by the solvent evaporation method. Three ratios of drug to carrier were prepared, namely the corresponding labels SD (1), SD (2), and SD (3): 0.5, 1:1, and 1:1.5. Ibuprofen and mucilage were melted in a beaker at 80°C under a water bath as they were swirled for five minutes with a glass rod to facilitate uniform mixing. The blend was ground in a mortar, sieved on a 30-mesh sieve, and subsequently put in screw-cap vials at room temperature under a desiccator for subsequent testing after it was quickly chilled in an ice bath for five minutes to become solid.⁴¹

Physical Mixture Preparation

The same drug-to-carrier ratios (1:0.5, 1:1, and 1:1.5) were employed to prepare physical mixes, which were labeled PM (1), PM (2), and PM (3), respectively. In order to ensure uniformity, ibuprofen and tamarind mucilage were manually mixed in a mortar for ten minutes. After sieving through a 30-mesh screen, the resulting powder was stored at room temperature in screw-cap vials such that it would be compared to the solid dispersions.⁴²

Table 5.3: shows formulation batch table for your solid dispersion (SD) and physical mixture (PM) preparations:

Batch Code	Ibuprofen (mg)	Tamarind Seed Mucilage (mg)	Method
SD (1) 1/0.5	1000	500	Solvent Evaporation
SD (2) 1/1	1000	1000	Solvent Evaporation
SD (3) 1/1.5	1000	1500	Solvent Evaporation
PM (1) 1/0.5	1000	500	Physical Mixing

PM (2) 1/1	1000	1000	Physical Mixing
PM (3) 1/1.5	1000	1500	Physical Mixing

5.4. Pre-formulation Studies

1. XRD Analysis

By analyzing how X-rays scatter off atomic planes, XRD is a non-destructive technique that can reveal a material's crystalline structure, phase purity, and lattice structure. It helps in recognizing crystalline or amorphous drugs, detect polymorphic changes, and determine excipient compatibility all essential in enhancing solubility in amorphous types—in pharmaceutical investigation.

2. FTIR

FTIR detects certain chemical groups in a molecule and looks for drug-excipient interactions. Researchers verify the medicine's structural integrity and make sure no unintended chemical reactions happened during formulation by comparing the spectra of the pure drug, excipients, and final formulation.

3. Screening for phytochemicals

To assess the therapeutic potential of plant constituents, phytochemical screening tests identify bioactive plant metabolites like alkaloids, flavonoids, and tannins. These qualitative tests justify the presence of secondary metabolites based on the expected pharmacological benefits of the drug.

4. Micrometric Properties

4.1 Density of Bulk

The weight of a powder is divided by the volume it occupies to obtain its bulk density. A graduated cylinder is gently packed with powder and the volume that the powder occupies naturally is measured.

4.2 Density Tapped

The tightness of a powder's settling after mechanical tapping is quantified by its "tapped density." Density is calculated by filling a certain amount of powder into a cylinder, tapping it 100 times, and measuring the resulting volume.

4.3 Repose Angle

Spilling 100 grams of powder through a stationary funnel onto a horizontal surface to form a conical heap is how this test measures powder flow. To determine flowability, the angle between the pile's slope and the horizontal is measured.

4.4 Carr Index

This index is used to compare the tapped and bulk densities to measure the compressibility and flow of a powder. Improved flow is represented by low numbers, which aids in formulation design.

5.5. Post-formulation

1. Zeta Potential and Particle Size

Zeta potential and particle size are determined in the formulation by Dynamic Light Scattering (DLS). Optimal nanocarriers are <200 nm. Surface charge is represented by zeta potential, and larger absolute values represent enhanced stability and fewer aggregations of particles.

4. Drug Loading and Encapsulation

Spectroscopy and extraction are employed to determine the drug's loading into the gel matrix. High encapsulation efficiency and uniform loading are ensured for consistent therapeutic action and controlled release.

5. Dissolution

Three solvents—0.1 N HCl, phosphate buffer solution (pH 7.2), and distilled water—were employed to measure solubility. In screw-top tubes, 10 mL of each solvent were combined with quantities of samples equivalent to 100 mg of ibuprofen (pure or solid dispersion), swirled end-over-end constantly for 24 hours, and filtered. To find out the concentration of the drug, a UV-Visible spectrophotometer was employed to find absorbance at 221 nm after a 1 mL aliquot of filtrate had been diluted.

6. In Vitro Dissolution

A USP Type II (paddle) equipment was utilized for the dissolution experiments, along with 900 mL of either 0.1 N HCl or phosphate buffer (pH 7.2) at $37 \pm 0.5^\circ\text{C}$. Paddles revolved at 50 rpm while samples containing 100 mg of ibuprofen were added. Five milliliters of samples were withdrawn at five, ten, twenty, thirty, forty-five, and sixty minutes, and replaced with fresh medium. The absorbance at 221 nm was determined. A standard curve was employed to determine the percentage of drug release.

Release behavior was analyzed with the following kinetic parameters:

- **T_{50%}**: Time for 50% drug release
- **T_{80%}**: Time for 80% release
- **Mean Dissolution Time (MDT)**: Average time for drug dissolution

These were calculated using:

- $T_{50\%} = (0.5/k)^{1/n}$
- $T_{80\%} = (0.8/k)^{1/n}$
- $MDT = (n/(n+1)) * k^{(-1/n)}$

A higher MDT indicates slower release, valuable for controlled-release formulations.

RESULT AND DISCUSSION**6.1. Pre-Formulation Studies****1. Phytochemical Screening**

The phytochemical analysis in table 6.1 of tamarind seed mucilage confirms the presence of carbohydrates, reducing sugars, glycosides, tannins, saponins, and phenolic compounds. Proteins and mucilage are also detected, with mucilage being strongly present. Alkaloids and flavonoids are absent, indicating a lack of significant nitrogen-containing or flavonoid-based compounds.

Table 6.1: Shows the phytochemical screening of the Tamarind seed mucilage

Phytochemical Test	Inference
Carbohydrates	+
Reducing Sugars	+

Proteins & Amino Acids	+
Glycosides	+
Alkaloids	-
Flavonoids	-
Tannins	+
Saponins	+
Phenolic Compounds	+
Mucilage	++

2. FTIR spectra

The FTIR spectrum in fig 6.1 of tamarind seed mucilage displays characteristic peaks corresponding to various functional groups. The broad peak at 3310 cm^{-1} indicates the presence of hydroxyl (-OH) groups, suggesting polysaccharides. The peaks at 2913 cm^{-1} correspond to C-H stretching, while the bands at 1610 cm^{-1} and 1525 cm^{-1} are associated with C=O and C=C stretching, indicative of carboxyl or aromatic groups. The peaks between $1150\text{--}897\text{ cm}^{-1}$ confirm the presence of glycosidic linkages and saccharide structures.

3. XRD spectra

The X-ray diffraction (XRD) pattern shown in fig 6.2 of ibuprofen shows multiple peaks, with a prominent peak at $22.41^\circ 2\theta$, indicating semi-crystalline nature. Other peaks at 16.10° , 20.26° , 25.17° , and $31.07^\circ 2\theta$ suggest the presence of ordered molecular structures. The broad and diffused peaks imply a mixture of amorphous and crystalline regions within the mucilage.

6.2. Post Formulation

1. Zeta Potential and Particle Size

The outcome of the particle size and zeta potential revealed in table 6.2, fig 6.3 and 6.4 that increased tamarind seed mucilage generated smaller particles and more stable particles. With the zeta potential of -21.7 mV and maximum particle size of 198.4 nm , batch SD (1) had the minimum mucilage content. The smallest particles, 158.2 nm , and the highest zeta potential, -27.8 mV , were produced by Batch SD (3), which contained the highest mucilage concentration. These findings suggest that increased mucilage enhances the effectiveness of the formulation by increasing colloidal stability and decreasing particle size.

2. Drug Loading and Encapsulation Efficiency

Drug loading decreased with increasing mucilage content, whereas encapsulation efficiency increased as shown in table 6.3, fig 6.5 and fig 6.6. Batch SD (1) had the lowest content of mucilage with an encapsulation efficiency of 85.40% and the highest drug loading of 66.67% .

The batch that was most mucilaginous, Batch SD (3), on the contrary, possessed the lowest drug loading at 40% but the highest encapsulation efficiency at 93.80%. This trend highlights the compromise between the amount of carriers and the drug's ability to be trapped effectively within the matrix.

3. SEM

The SEM images in fig 6.7 display the surface morphology of tamarind seed mucilage-based solid dispersion of ibuprofen. The left image shows a more uniform and finely distributed particle structure, indicating better dispersion and reduced crystallinity. The right image presents larger, irregularly shaped particles with some crystalline characteristics. These changes confirm successful transformation of ibuprofen into an amorphous form within the mucilage matrix, enhancing its solubility and dissolution potential. The homogeneous distribution suggests efficient drug-polymer interaction in the solid dispersion system.

4. Dissolution Efficiency

The dissolution results shown in table 6.4 and fig 6.8 conclusively show that, in comparison to physical mixtures and the pure drug, solid dispersions prepared with tamarind seed mucilage significantly enhance ibuprofen's release rate. At a drug-to-mucilage ratio of 1:1.5, SD (3) surpassed the other formulations, releasing 99.8% of the drug within 60 minutes and achieving a $T_{50\%}$ of 10.8 minutes. This rapid and efficient release illustrates how the solubility and potential bioavailability of ibuprofen are both increased when it is formulated as a perfect solid dispersion.

7. Stability studies

All preparations showed in table 6.6 had good stability at the start of the study, having high drug content and good release efficiency. Solid dispersions (SDs) performed better than others; SD (3), with a drug-to-mucilage ratio of 1:1.5, recorded a remarkable 99.8% release in 60 minutes and 98.9% drug content. Physical mixtures (PMs) also showed good performance, having a drug content of more than 97% but a relatively lower release efficiency. At 64.3%, neat ibuprofen exhibited the lowest release rate with 99% of its substance remaining. The excellent initial quality and integrity of the formulations were confirmed by physical stability of all samples, with no indication of discoloration or clumping.

Discussion

By developing solid dispersions with tamarind seed mucilage as a hydrophilic, natural carrier, this study sought to enhance the dissolution and solubility of ibuprofen, which is a BCS Class II drug with limited water solubility. These dispersions were also analyzed at various drug-to-mucilage ratios along with physical blends and neat ibuprofen as controls.

The potential of tamarind mucilage as a good polymer carrier was ascertained through phytochemical analysis, where significant constituents like tannins, saponins, glycosides, and mucilage were identified. Ibuprofen and the mucilage were not chemically interactive, based on FTIR analysis, but XRD and DSC analysis showed that ibuprofen was converted to amorphous state, which plays a significant role in enhancing rates of dissolving.

Greater mucilage ratios yielded more minute particles and greater colloidal stability, based on particle size tests and zeta potential tests; SD (3) with a ratio of 1:1.5 showed optimum results. Enhanced drug release came from these physical improvements. Solid dispersions were greatly

superior to physical blends and individual ibuprofen in in vitro dissolution studies; SD (3) yielded the fastest $T_{50\%}$, greatest dissolution efficiency, and a release of 99.8% at 60 minutes. This highlights the role of increased mucilage in enhancing solubility and release kinetics.

Drug loading reduced when mucilage concentration was greater, yet encapsulation efficiency improved, reflecting a compromise between drug loading and carrier amount. Optimization of the drug delivery system involves such a compromise. Good drug content, release performance, and physical stability were ensured by solid dispersions, as per six-month stability tests under accelerated conditions (40°C, 75% relative humidity). In contrast, physical blends progressively exhibited decreased release efficiency and mild clumping.

In general, this research indicates that ibuprofen solubility, stability, and dissolution may be increased efficiently, economically, and ecologically soundly by solid dispersions based on tamarind seed mucilage. The findings usher in the promise of enhanced oral bioavailability of low-solubility drugs; additional pharmacokinetic and clinical investigations are recommended to ensure practical efficacy.

Conclusion

To enhance the dissolution and solubility of ibuprofen, a BCS Class II drug with poor water solubility, this research successfully showcased the viability of tamarind seed mucilage as a green, natural carrier for solid dispersions. Because poor solubility tends to limit the efficacy of a drug, this study employed solvent evaporation as part of a co-solvency-based approach. Three drug-to-mucilage ratios were employed to form solid dispersions, which were compared to physical blends and neat ibuprofen. Phytochemistry tests validated the medicinal excipient value of the tamarind seed by verifying the existence of therapeutic compounds like tannins, glycosides, and mucilage. FTIR, XRD, and SEM were some of the analytical methods that verified ibuprofen's conversion to an amorphous state, which is important for solubility enhancement. Aside from possessing the smallest particle size, highest zeta potential, and optimum encapsulation efficiency—all of which reflect outstanding stability and uniformity—the SD (3) formulation, with a 1:1.5 ratio, was also remarkable for releasing nearly 100% of the drug in 60 minutes. Increased mucilage content was evidently associated with enhanced drug release in in vitro dissolution tests, surpassing physical blends and the free drug by a wide margin. Solid dispersions were stable and retained their performance and integrity over the duration of six months of stability tests at elevated temperatures (40°C and 75% relative humidity), whereas physical blends exhibited signs of degradation. The findings show that tamarind seed mucilage is a cost-effective, sustainable, and safe option to enhance the bioavailability of poorly soluble drugs, particularly for oral administration.

Future Scope

This research's promising results leave the door open to intriguing new investigations. The ability of tamarind seed mucilage to enhance ibuprofen solubility is strongly supported by in vitro data; however, in vivo studies in humans and animals must be done to confirm increases in absorption and therapeutic effects. Another very important area is scaling up the formulation process for industrial application, which involves research into its feasibility, homogeneity, and compliance with manufacturing requirements. Although tamarind mucilage is generally innocuous, comprehensive toxicological studies are vital in order to establish that it is safe for use over the long term and also comply with legal requirements. Through implementation of this

approach to additional BCS Class II and IV drugs, tamarind mucilage can potentially emerge as a versatile solubility enhancer. Moreover, the therapeutic use of the formulation and its capability to address diverse patient needs could be further widened by reformulating it into an assortment of dosage forms, e.g., tablets, capsules, buccal gels, or controlled-release devices. Standardizing tamarind mucilage as a drug excipient and developing strict criteria for its properties and processing to ensure quality and facilitate regulatory approval are the most important steps toward making it possible for its widespread use. Through these steps, this natural carrier can be a viable, sustainable means of improving the efficacy of poorly soluble drugs in both clinical and commercial applications.

Reference

1. Ajjarapu, S., Banda, S., Basim, P., & Dudhipala, N. (2022). Melt fusion techniques for solubility enhancement: A comparison of hot melt extrusion and KinetiSol® technologies. *Scientia Pharmaceutica*, 90(3), 51–59. <https://doi.org/10.3390/scipharm90030051>
2. Akbarpour Nikghalb, L., Singh, G., Singh, G., & Fazaeli Kahkeshan, K. (2012). Solid dispersion: Methods and polymers to increase the solubility of poorly soluble drugs. *Journal of Applied Pharmaceutical Science*, 2(10), 170–175. <https://doi.org/10.7324/JAPS.2012.21031>
3. Sakure K, Thakur AS, Pradhan M, Verma VS, Badwaik H. *Development and evaluation of a plumbagin-brinzolamide binary cocrystals for improved aqueous solubility*. Journal of Pharma Insights and Research. 2026;4(2):159–166.
4. Bindhani, S., & Mohapatra, S. (2018). Recent approaches of solid dispersion: A new concept toward oral bioavailability. *Asian Journal of Pharmaceutical and Clinical Research*, 11(2), 72–78. <https://doi.org/10.22159/ajpcr.2018.v11i2.23161>
5. Kashyap G, Pandey AP, Sahu MK, Lal B, Verma VS. *Biodegradable polymers in drug delivery: Design, degradation, and drug release dynamics*. Journal of Pharmaceutical Research and Integrated Medical Sciences. 2026:26–43.
6. Bushra, R., & Aslam, N. (2010). Drug interactions and their clinical significance. *Oman Medical Journal*, 25(3), 155–161. <https://doi.org/10.5001/omj.2010.49>
7. Verma VS, Sakure K, Badwaik HR. *Xanthan gum a versatile biopolymer: Current status and future prospectus in hydrogel drug delivery*. Current Chemical Biology. 2017;11(1):10–20.
8. Chavan, S., Patel, K., Shelar, D., & Vavia, P. (2013). Preparation of oxcarbazepine solid dispersion by hot melt extrusion for enhanced dissolution: Downstream processing to tablets. *American Journal of PharmTech Research*, 3(1).
9. Chiou, W. L., & Riegelman, S. (1971). Pharmaceutical applications of solid dispersion systems. *Journal of Pharmaceutical Sciences*, 60(9), 1281–1302. <https://doi.org/10.1002/jps.2600600902>

10. Corum, I., Spangenberg, A., Miller, K., Kucera, S., & Miller, D. (2023). Minimization of acid-catalyzed degradation in KinetiSol processing through HPMCAS neutralization. *Molecular Pharmaceutics*, 20(5), 1599–1612.
11. Craig, D. Q. (2002). The mechanisms of drug release from solid dispersions in water-soluble polymers. *International Journal of Pharmaceutics*, 231(2), 131–144. [https://doi.org/10.1016/S0378-5173\(01\)00891-2](https://doi.org/10.1016/S0378-5173(01)00891-2)
12. De Mohac, L. M., Caruana, R., Cavallaro, G., Giammona, G., & Licciardi, M. (2020). Spray-drying, solvent-casting and freeze-drying techniques: A comparative study on their suitability for the enhancement of drug dissolution rates. *Pharmaceutical Research*, 37, 1–8.
13. Deac, A., Qi, Q., Indulkar, A. S., Purohit, H. S., Gao, Y., & Zhang, G. G. Z. (2023). Dissolution mechanisms of amorphous solid dispersions: Role of drug load and molecular interactions. *Molecular Pharmaceutics*, 20(4), 722–737. <https://doi.org/10.1021/acs.molpharmaceut.2c00892>
14. Desai, D., Wang, J., Wen, H., Li, X., & Timmins, P. (2013). Formulation design, challenges, and development considerations for fixed dose combination (FDC) of oral solid dosage forms. *Pharmaceutical Development and Technology*, 18(6), 1265–1276. <https://doi.org/10.3109/10837450.2012.660699>
15. Di, L., Fish, P. V., & Mano, T. (2012). Bridging solubility between drug discovery and development. *Drug Discovery Today*, 17(9–10), 486–495. <https://doi.org/10.1016/j.drudis.2011.11.007>
16. Di Martino, R. M. C., Maxwell, B. D., & Pirali, T. (2023). Deuterium in drug discovery: Progress, opportunities and challenges. *Nature Reviews Drug Discovery*, 22(8), 562–584. <https://doi.org/10.1038/s41573-023-00703-8>
17. Dieringer, T. D., Schaenman, J. M., & Davis, M. R. (2022). Enteral feeding tube administration with therapeutic drug monitoring. *Journal of Antimicrobial Chemotherapy*, 77(5), 1417–1423. <https://doi.org/10.1093/jac/dkac035>
18. Dinunzio, J. C., Schilling, S. U., Coney, A. W., Hughey, J. R., Kaneko, N., & McGinity, J. W. (2012). Use of highly compressible microcrystalline cellulose. *Drug Development and Industrial Pharmacy*, 38(2), 180–189. <https://doi.org/10.3109/03639045.2011.595415>
19. Dohrn, S., Rawal, P., Luebbert, C., et al. (2021). Predicting process design spaces for spray drying amorphous solid dispersions. *International Journal of Pharmaceutics X*, 3, 100072. <https://doi.org/10.1016/j.ijpx.2021.100072>
20. Duong, T. V., & Van den Mooter, G. (2016). The role of the carrier in the formulation of pharmaceutical solid dispersions. Part I: Crystalline and semi-crystalline carriers. *Expert Opinion on Drug Delivery*, 13(11), 1583–1594. <https://doi.org/10.1080/17425247.2016.1198768>
21. Sahu P, Sharma G, Verma VS, Mishra A, Chauhan P. *Statistical optimization of microwave assisted acrylamide grafting of Linum usitatissimum gum*. *NeuroQuantology*. 2022;20(11):4008–4026.

22. Huang, S., & Williams, R. O. (2018). Effects of the preparation process on the properties of amorphous solid dispersions. *AAPS PharmSciTech*, 19(5), 1971–1984. <https://doi.org/10.1208/s12249-017-0861-7>
23. Ingle, U. S., Gaikwad, P. D., Bankar, V. H., et al. (2011). A review on solid dispersion: A dissolution enhancement technique. *International Journal of Research in Ayurveda and Pharmacy*, 2(3), 751–757.
24. Dey VD, Verma VS, Pandey AP, Gupta N, Chandrakar JC, Yadav PK. *Green pharmaceutical manufacturing: A focus on sustainable approaches to drug formulation development, production & case studies*. Indian Journal of Pharmaceutical Chemistry and Analytical Techniques. 2025:1–20.
25. Sharma G, Verma VS, Sharma M, Chandrakar S, Gupta S, Solanki H, et al. *Formulation and evaluation of extended release tablets of diltiazem hydrochloride*. Research Journal of Pharmacy and Technology. 2016;9(7):782–788.
26. Jo, K., Cho, J. M., Lee, H., Kim, E. K., Kim, H. C., Kim, H., & Lee, J. (2018). Enhancement of aqueous solubility and dissolution of celecoxib through phosphatidylcholine-based dispersion systems solidified with adsorbent carriers. *Pharmaceutics*, 11(1), 18. <https://doi.org/10.3390/pharmaceutics11010018>
27. Kalepu, S., & Nekkanti, V. (2016). Improved delivery of poorly soluble compounds using nanoparticle technology: A review. *Drug Delivery and Translational Research*, 6, 319–332. <https://doi.org/10.1007/s13346-016-0287-0>
28. Kesisoglou, F., Basu, S., Belubbi, T., et al. (2023). Streamlining food effect assessment—Are repeated food effect studies needed? An IQ analysis. *AAPS Journal*, 25(4), 60–67. <https://doi.org/10.1208/s12248-023-00814-4>
29. Khan, G. M., & Jiabi, Z. (1998). Solid dispersion systems: Applications and limitations. *Drug Development and Industrial Pharmacy*, 24(5), 455–462. <https://doi.org/10.3109/03639049809085643>
30. Kim, K. T., Lee, J. Y., Lee, M. Y., Song, C. K., Choi, J., & Kim, D. D. (2011). Solid dispersions as a drug delivery system. *Journal of Pharmaceutical Investigation*, 41(3), 125–142. <https://doi.org/10.4333/KPS.2011.41.3.125>
31. Kumar, G. P., & Rajeshwarrao, P. (2011). Nonionic surfactant vesicular systems for effective drug delivery. *Acta Pharmaceutica Sinica B*, 1(4), 208–219. <https://doi.org/10.1016/j.apsb.2011.09.002>
32. Lankalapalli, S., Beeraka, N. M., & Bulusu, B. T. (2018). Studies on oral bioavailability enhancement of itraconazole salts. *International Journal of Research in Pharmaceutical Chemistry*, 8(1), 131–143.
33. Leuner, C., & Dressman, J. (2000). Improving drug solubility for oral delivery using solid dispersions. *European Journal of Pharmaceutics and Biopharmaceutics*, 50(1), 47–60. [https://doi.org/10.1016/S0939-6411\(00\)00076-X](https://doi.org/10.1016/S0939-6411(00)00076-X)
34. Maincent, J., & Williams, R. O. (2018). Sustained-release amorphous solid dispersions. *Drug Delivery and Translational Research*, 8(6), 1714–1725. <https://doi.org/10.1007/s13346-018-0494-8>

35. Marques, C. S. F., Rezende, P., Andrade, L. N., et al. (2018). Solid dispersion of praziquantel enhanced solubility and efficacy. *Journal of Drug Delivery Science and Technology*, 45, 124–134. <https://doi.org/10.1016/j.jddst.2018.03.009>
36. Meng, F., Gala, U., & Chauhan, H. (2015). Classification of solid dispersions. *Drug Development and Industrial Pharmacy*, 41(9), 1401–1415. <https://doi.org/10.3109/03639045.2015.1018274>
37. Okonogi, S., Oguchi, T., Yonemochi, E., Puttipipatkachorn, S., & Yamamoto, K. (1997). Improved dissolution of ofloxacin via solid dispersion. *International Journal of Pharmaceutics*, 156(2), 175–180. [https://doi.org/10.1016/S0378-5173\(97\)00196-8](https://doi.org/10.1016/S0378-5173(97)00196-8)
38. Pawar, A. R., Mundhe, P. V., Deshmukh, V. K., et al. (2021). Enrichment of aqueous solubility of mesalamine. *Journal of Pharmaceutical and Biological Sciences*, 9(2), 127–135.
39. Pouton, C. W. (2000). Lipid formulations for oral administration. *European Journal of Pharmaceutical Sciences*, 2(Suppl. 2), 93–98.
40. Verma VS, Badwaik HR, Vaishnav Y, Alexander A, A A. Synthesis, Characterization, Molecular Modelling and Biological Evaluation of Substituted Benzo (h) Chromene-3-Carboxylate Derivatives as a Potential Agent for the Treatment of Hyperlipidemia. *Indian J Pharm Sci.* 2022;84(2). doi:10.36468/PHARMACEUTICAL-SCIENCES.939
41. Rasool, A. A., Hussain, A. A., & Dittert, L. W. (1991). Solubility enhancement techniques. *Journal of Pharmaceutical Sciences*, 80(4), 387–393. <https://doi.org/10.1002/jps.2600800422>
42. *Remington: The science and practice of pharmacy* (21st ed.). (n.d.). Lippincott Williams & Wilkins.