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ORIGINAL RESEARCH

RETRACTED ARTICLE: Berberine nanoparticles with enhanced in vitro bioavailability: characterization and antimicrobial activity

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Background: Berberine is an isoquinoline alkaloid widely used in Ayurveda and traditional Chinese medicine to treat illnesses such as hypertension and inflammatory conditions, and as an anticancer and hepato-protective agent. Berberine has low oral bioavailability due to poor aqueous solubility and insufficient dissolution rate, which can reduce the efficacy of drugs taken orally. In this study, evaporative precipitation of nanosuspension (EPN) and anti-solvent precipitation with a syringe pump (APSP) were used to address the problems of solubility, dissolution rate and bioavailability of berberine.

Methods: Semi-crystalline nanoparticles (NPs) of 90–110 nm diameter for APSP and 65–75 nm diameter for EPN were prepared and then characterized using differential scanning calorimetry (DSC) and X-ray powder diffractometry (XRD). Thereafter, drug content solubility and dissolution studies were undertaken. Berberine and its NPs were evaluated for their antibacterial activity.

Results: The results indicate that the NPs have significantly increased solubility and dissolution rate due to conversion of the crystalline structure to a semi-crystalline form.

Conclusion: Berberine NPs produced by both APSP and EPN methods have shown promising activities against Gram-positive and Gram-negative bacteria, and yeasts, with NPs prepared through the EPN method showing superior results compared to those made with the APSP method and the unprocessed drug.

Keywords: berberine, EPN, APSP, bioavailability, dissolution, antibacterial activity, precipitation method

Introduction

In pharmaceuticals, solubility is one of the main factors that keeps many potential drug molecules from the market. Poor aqueous solubility affects bioavailability, due to reduced dissolution of the drug in the body, which leads to poor drug absorption, and thus the desired plasma concentration is not achieved to cause pharmacological action.[1] Problems with solubility result in increased costs, as a much higher dose is needed to reach the required plasma concentration level. Moreover, higher doses result in undesired pharmacological responses, such as more adverse effects and poor patient compliance, when the outcome is not what a patient expects.[2,3]

Solid dosage forms like tablets and capsules, when administered orally, first undergo dissolution in gastrointestinal fluids prior to absorption. For less soluble drugs, the dissolution rate limits the bioavailability. To develop a suitable dosage form, many difficulties arise due to the poor water solubility of drugs, as the therapeutic efficacy of a drug depends upon the solubility of drug molecules.[4]

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Many approaches have been adopted to solve the problems of poor solubility and decreased bioavailability. To improve solubility, some of the techniques that have been used so far are particle-size reduction, solid dispersion, and presentation of a drug in the form of nanoparticles (NPs). NPs are smaller in size than conventional drug particles, and so there is increased drug surface area.[5–7]

Drug nanocrystals can be produced by several techniques, including "top-down" and "bottom-up" approaches.[8,9] Top-down methods are used frequently in the pharmaceutical industry, and include milling and high-pressure homogenization,[10,11] while bottom-up approaches, eg, supercritical fluid technology, antisolvent precipitation, and spray freezing into liquid, are used less commonly. Among the bottom-up approaches, the antisolvent precipitation method is an easy, simple and cost-effective way to achieve a nano scale.[12–14] If a drug is soluble in an organic solvent, precipitation would be a feasible method.[10] Evaporative precipitation of nanosuspension (EPN) and anti-solvent precipitation with a syringe pump (APSP) are among the approaches that are used to address the problems of solubility, dissolution rate and bioavailability.[11,15] Fessi et al first developed and patented a solvent displacement method for the simple and rapid preparation of a nanosuspension as presented by Bilati et al.[12]

Phospholipid carriers have become an attractive tool to address the issue of poorly water-soluble active pharmaceutical ingredients.[16] Phytosomes have emerged as a delivery technology to incorporate phytoconstituents into phospholipid complexes, with subsequent improvement in bioavailability and absorption of poorly soluble compounds.

Berberine (BBR) is an isoquinoline alkaloid found in the stem bark and roots of *Berberis aristata* (family Berberidaceae), commonly known as "Daru haldi" in Urdu. BBR formulations are widely used in Ayurveda and traditional Chinese medicine[18] to treat illnesses like hypertension[19] and inflammatory conditions.[20,21] BBR has also been reported to have a number of pharmacological actions including antimalarial,[22] anti-arrhythmic,[23,24] anti-hyperglycemic,[19] anticancer,[25–27] hepato-protective,[28] antioxidant,[29] and antimicrobial.[30,31] However, the poor water solubility of BBR impacts its dissolution rate and oral bioavailability, thus limiting its clinical use.[1–5] BBR appears to be a hydrophilic compound and has a log *P*-value of −1.5,[32] which makes BBR a class III drug in the biopharmaceutical classification system (BCS). Drugs included in this class are lipophobic and have poor membrane permeability, and the absorption of the drugs is mostly limited to the paracellular pathway. This limits intestinal absorption and leads to low bioavailability.[33]

BBR NPs were prepared using APSP and EPN methods in order to improve the bioavailability of the drug. The prepared NPs were investigated for parameters including dissolution, solubility, and antimicrobial properties.

Materials and methods

Materials

All the chemicals utilized in this study were of analytical grade from Sigma-Aldrich Co. (St Louis, MO, USA). Unprocessed BBR powder was received as a kind gift from Dr Javed Ali, Department of Microbiology, Pakistan Council of Scientific and Industrial Research (PCSIR) Laboratories, Peshawar, Pakistan. Ethanol, n-hexane, potassium phosphate monobasic, sodium hydroxide, HCl (35.5% w/v), hydroxy propyl methyl cellulose (HPMC), and propylene glycol (PG) were also from Sigma-Aldrich Co, while the deionized double distilled water used in this work was obtained using the Millipore Q® system (EMD Millipore, Billerica, MA, USA).

Methods

Preparation of BBR NPs

BBR NPs were prepared through previously described EPN and APSP methods with slight modification for this study.[11] Briefly, in the APSP method, a solvent (ethanol) was used to prepare a saturated solution of BBR which was rapidly injected into a particular volume of deionized water (anti-solvent) at a fixed flow rate of 1 mL/min under mechanical stirring (3,000 rpm), with the help of a syringe. The same procedure was used while incorporating different volumes of the deionized water with the same volume of saturated drug solution (1:10, 1:15, 1:20 v/v). After stirring, the resulting mixture, which was in the form of a turbid/opaque suspension, was evaporated quickly in a vacuum using a rotary evaporator to obtain nano-sized drug particles.[11]

In EPN, a pure drug saturated solution was prepared in ethanol and then, as a result of the quick addition of hexane (anti-solvent) to the prepared drug solution, a nanosuspension was formed. Different solvent:anti-solvent ratios (1:10, 1:15, 1:20 v/v) were used. Nano-sized drug particles from a nanosuspension were obtained by rapid evaporation of the solvent and anti-solvent in a vacuum.[11] HPMC and PG at a concentration of 1% were used as stabilizers for NP preparation by both methods.

Characterization

The prepared NPs were characterized using Fourier-transform infrared spectroscopy (FTIR) for structure confirmation, scanning electron microscopy (SEM) for surface morphology and particle size, X-ray diffraction (XRD) for the determination

of structure lattice, and differential scanning calorimetry (DSC) to study the thermal behavior of the sample.

BBR NPs were characterized to determine their particle size and associated polydispersity index (PDI) by dynamic light scattering (Zetasizer® NanoS, Malvern Instruments, Malvern, UK). All the samples were analyzed in triplicate (n=3), and results were presented as mean ± SD.

FTIR was performed in the range of 4,400–200 cm^{-1} using an infrared spectrophotometer (IR Prestige-21 Fourier-transform infrared spectrophotometer, Shimadzu, Kyoto, Japan) in the range of 200–4,400 cm^{-1}.

Electron photomicrographs of NPs prepared by APSP and EPN were obtained by SEM (JEOL JSM-5910, Tokyo, Japan), which was operated at 20 kV using the standard procedure for sample preparation.

The XRD patterns of unprocessed BBR and prepared NPs were recorded using an X'Pert PRO X-ray diffractometer (PANalytical, Almelo, the Netherlands). The operating voltage was 40 kV, operating current was 30 mA, the start angle 2θ was 5° and the finishing angle was 60°.

DSC studies were done using Mettler-Toledo 822e (Greifensee, Switzerland). The procedure involved using ~3–6 mg of sealed sample in one pan while an empty pan served as a standard. Heat flow to both pans was provided at a rate of 10°C/min under nitrogen gas flow. Any change due to thermal effect in the pans was recorded.

In vitro analysis

Solubility studies

Solubility is the maximum amount of a compound/material in a solution for a particular solvent. The solubility of large particles (micrometers or more) is generally not dependent on particle size. However, the solubility of NPs mainly depends on particle size, with an increase of solubility as the particle size decreases.[34]

For the solubility study, a surplus amount (equivalent to 200 mg) of unprocessed BBR and the prepared NPs were placed in separate vials. Ten mL of distilled water was added to each vial and shaken vigorously in an orbital shaker (HS501 orbital shaker, IKA GmbH, Staufen im Breisgau, Germany) at 25°C (room temperature) for 72 hours at 3,000 rpm. After mixing, samples were centrifuged at 3,000 rpm and filtered through a Whatman filter paper no 1 (Thermo Fisher Scientific, Waltham, MA, USA). For determination of solubility, the filtered portion was diluted and analyzed at 263 nm using a UV-visible spectrophotometer (PharmaSpec 1,700 UV-visible spectrophotometer, Shimadzu). The same procedure was adopted for PBS pH 6.8 and 0.1 M HCl as solvents to determine the solubility. All tests were run in triplicate. The data were evaluated to determine their significance by applying statistical analysis (one-way ANOVA followed by Dunnett's post hoc test).

Dissolution

Three different dissolution media – distilled water, 0.1 M HCl, and PBS (pH 6.8) – were used in the dissolution studies in accordance with United States Pharmacopeia (USP) method II (paddle method) as reported previously, with slight modifications.[35–37] The volume used for each medium was 900 mL at 37°C±0.5°C at a rotation speed of 100 rpm. Unprocessed BBR (100 mg) and prepared NPs were subjected to the dissolution vessels. Five mL aliquots were drawn at predetermined intervals (15, 30, 45, 60, 90, and 120 minutes) and filtered through Whatman filter paper no 1. To maintain the sink conditions, the same volume of medium was replaced.[38] Filtered samples were suitably diluted and observed spectrophotometrically using a double-beam spectrophotometer (Agilent 8453 UV/visible spectrophotometer, Agilent Technologies, Santa Clara, CA, USA) at a maximum wavelength of 263 nm. All tests were conducted in triplicate.

Antimicrobial study

The NPs prepared by APSP and EPN methods were tested for their in vitro antimicrobial potentials against four bacteria – two Gram-positive (*Staphylococcus aureus* and *Bacillus subtilis*) and two Gram-negative (*Escherichia coli* and *Pseudomonas aeruginosa*) – as well as two yeasts (*Candida albicans* and *Candida glabrata*) using 96-well microtest plate methods in accordance with the Clinical and Laboratory Standards Institute guidelines[39] and a previously reported method.[40] The lowest concentration of test NPs that totally inhibited the growth of bacteria and yeasts was considered as the minimal inhibitory concentration (MIC; µg/mL) of the respective test NPs. Positive controls included norfloxacin (for Gram-negative bacteria), clarithromycin (for Gram-positive bacteria), and miconazole (for yeasts), while PBS was used as a vehicle for NP solutions from the respective methods.

Results and discussion

Characterization of the NPs prepared by APSP and EPN

NPs of BBR prepared by APSP and EPN methods were characterized by the following analytical techniques: SEM, Zetasizer, FTIR, DSC and XRD.

Surface morphology

SEM studies were carried out for unprocessed BBR, and its NPs were prepared by APSP (Figure 1) and EPN (Figure 2). The white patches in the figures show the formation of NPs

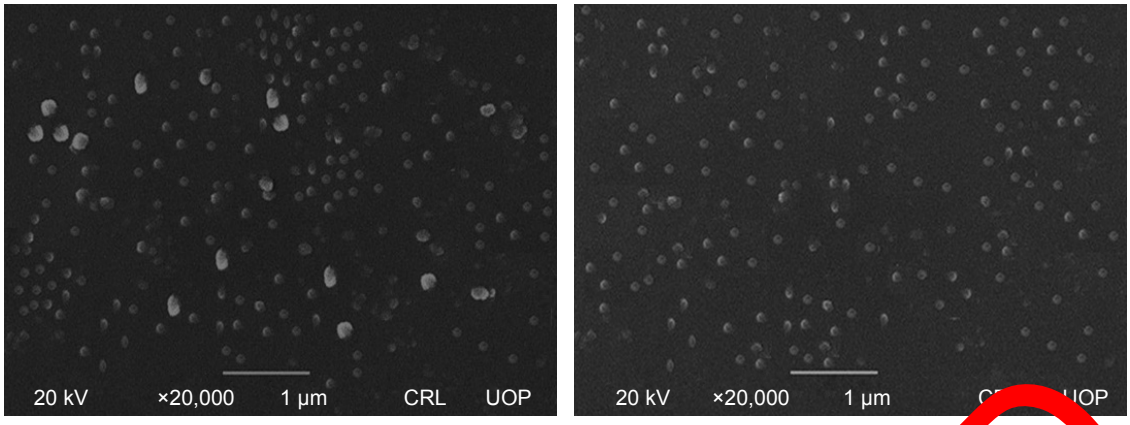

Figure 1 Scanning electron microscope images of berberine nanoparticles prepared by anti-solvent precipitation with a syringe pump.
Abbreviation: CRL UOP, Central Resource Lab, University of Peshawar.

with diameters of approximately 90–110 nm for APSP and 65–75 nm for EPN. The high surface area due to particle size reduction enhanced solubility, dissolution rate and the bioavailability of the NPs.

Particle size measurement

The mean particle sizes of BBR NPs prepared through APSP and EPN methods are represented in Figure 3A and 3B, respectively. Both figures represent mean particle size ranges from 50±5 nm to 170±7 nm. The mean particle size and PI values of NPs prepared by the EPN method was 71.53 nm while the NPs prepared by APSP method had a mean particle size of 102.62 nm. These values show that both NPs have narrow size distribution.

FTIR studies

FTIR spectra of unprocessed BBR (Figure 4A) and its NPs prepared by APSP (Figure 4B) and EPN (Figure 4C) indicate sharp peaks with proper intensities as the vibrational changes play a significant role in the intermolecular interactions in solid materials. In the FTIR spectra, the characteristic peaks are as follows: 700–1,3[illegible] cm^{-1} (skeletal C–C vibrations), 1,103.28 cm^{-1} (C–O), [illegible] cm^{-1}, and 1,504.48 cm^{-1} (aromatic C=C stretching), [illegible] cm^{-1} (skeleton vibration of aromatic C=C ring stretching), 1,386.82 cm^{-1} and 1,361.74 cm^{-1} (C=C stretching), 1,276.88 cm^{-1} (C–O–C stretching), and 1,035.7[illegible]1,184.29 cm^{-1} (in plane = C–H bending).[41]

X-ray diffractometry

The XRD pattern of unprocessed BBR (Figure 5) shows sharp and intense diffraction peaks at 2θ of 8.6°, 9.1°, 12.9°, 16.2°, 20.9°, 25.4°, and 30.1°, which indicates that unprocessed BBR is crystalline in nature. The NPs prepared by the APSP and EPN methods show diffraction peaks with less intensity, which is indicative of a change in the crystalline nature of the material (Figure 5). Less crystalline (semi-crystalline) and amorphous materials have greater free energy compared to their corresponding crystalline forms. Therefore, less crystalline or amorphous forms of the drugs can be more easily solubilized and have enhanced dissolution rates compared to their respective crystalline forms.[41–44]

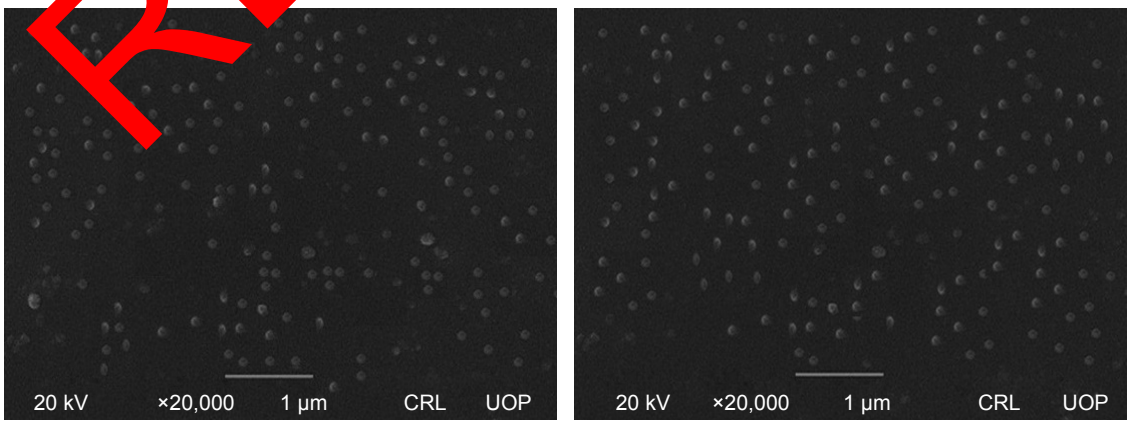

Figure 2 Scanning electron microscope images of berberine nanoparticles prepared by evaporative precipitation of nanosuspension.
Abbreviation: CRL UOP, Central Resource Lab, University of Peshawar.

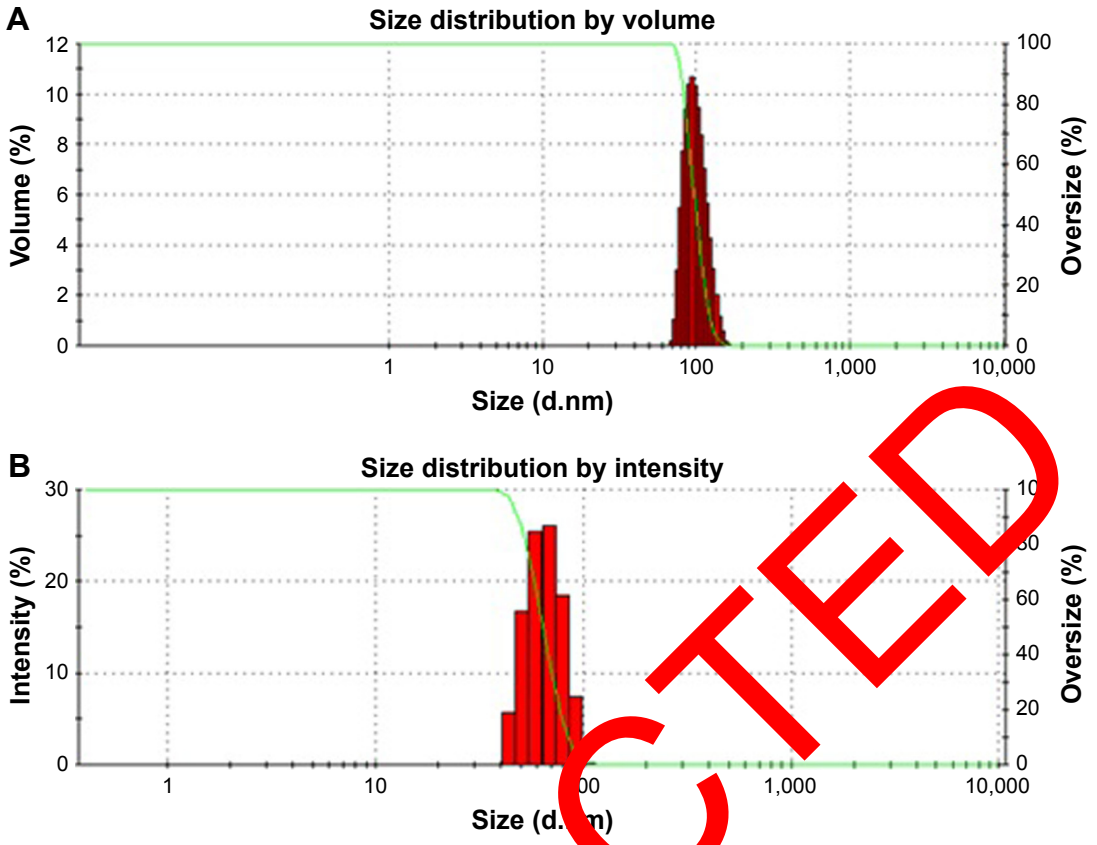

Figure 3 Particle size of the nanocrystals and associated polydispersity index of berberine nanoparticles prepared by (**A**) anti-solvent precipitation with a syringe pump; and (**B**) evaporative precipitation of nanosuspension.

Thus, modification in the crystalline nature through nano sizing may be an ideal approach for enhancement of solubility and dissolution rates of drug molecules, which will further improve bioavailability.[41]

Differential scanning calorimetry

NPs prepared by the APSP and EPN methods were further characterized by DSC to determine the effect of crystal structure during milling (Tm) on the heat enthalpy of unprocessed BBR and the prepared NPs (Figure 6). In the present study, unprocessed BBR showed a sharp endothermic peak showing melting of BBR at 145°C. Prepared NPs had almost the same melting point as that of the unprocessed drug, but the melting endothermic peak was less intense, with an enthalpy of heat fusion lower than the unprocessed drug. The reduction in the enthalpy values is an indication of reduction in crystallinity due to decrease in particle size.[41–43,45]

In vitro evaluation

Solubility studies

Next, the solubility of unprocessed BBR (Figure 7) and the prepared NPs in distilled water, 0.1 M HCl and PBS (pH 6.8) were studied. The results clearly indicate that solubility of BBR increases when converted to the nano form in all three solvents. The enhancement of the solubility may be attributed to the changes in the crystalline nature of BBR to a semi-crystalline or less crystalline form.[15,42,46–49] The nano form of BBR has more free energy compared to the micro form which further helps in improving the solubility of the NPs. It is evident from Figure 7 that the solubility of BBR in distilled water is very close to that of PBS (pH 6.8). The solubility of BBR in 0.1 M HCl was lower than that in distilled water and PBS (pH 6.8). The decrease in solubility in 0.1 M HCl solution may be due to conversion of BBR to berberine chloride, which is less soluble than BBR.

It was found that the solubility of the NPs was significantly higher ($P<0.001$) than the unprocessed BBR in the distilled water, 0.1 M HCl and PBS.

Dissolution studies

Dissolution studies of unprocessed BBR and of the NPs prepared by the APSP and EPN methods were carried out in distilled water (Figure 8A), PBS pH 6.8 (Figure 8B) and 0.1 M HCl (Figure 8C) over a period of 120 minutes. Samples were drawn at different time intervals (15, 30, 45, 60, 90, and 120 minutes). Dissolution rate analysis

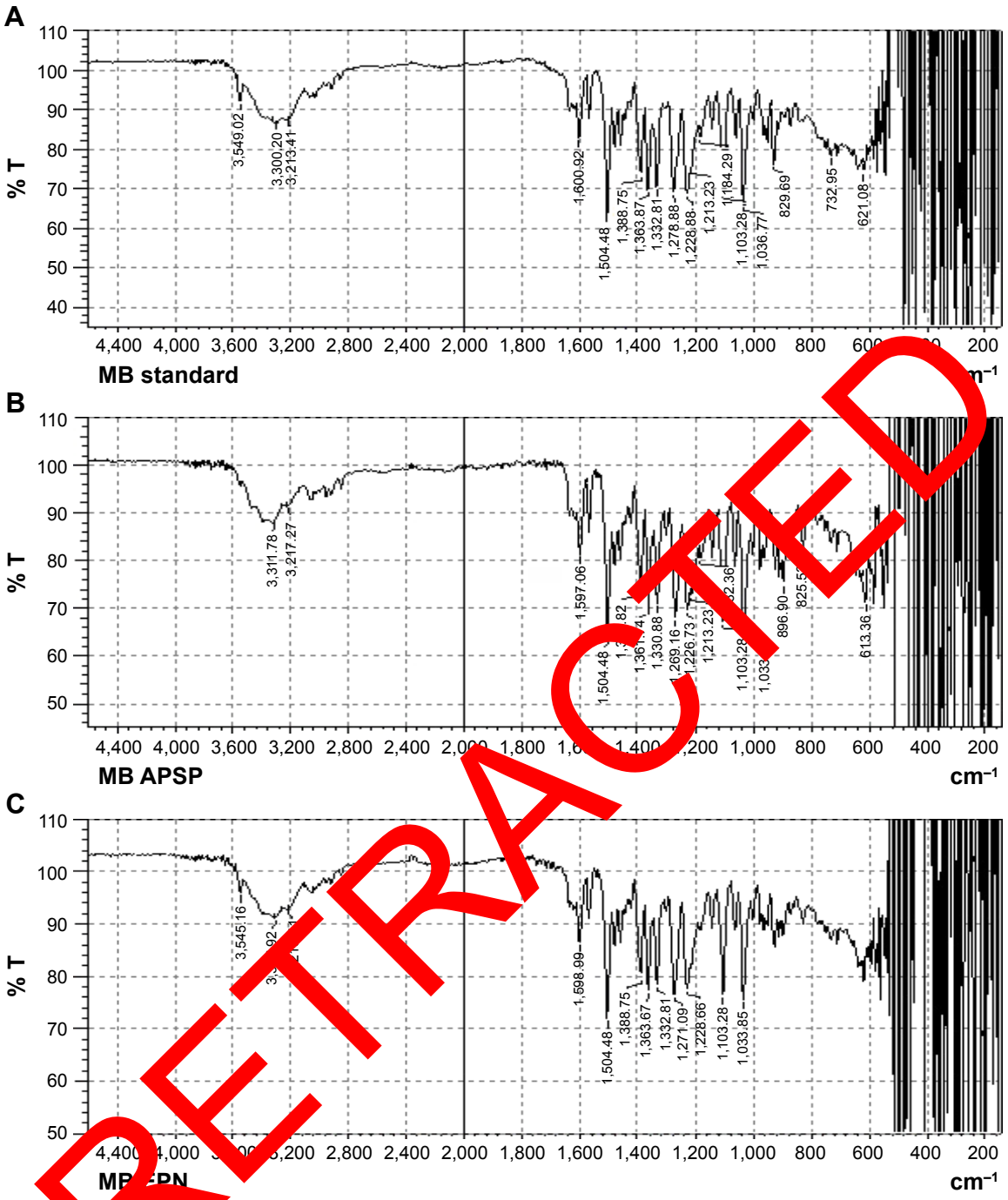

Figure 4 Fourier-transform infrared spectroscopy spectra of (**A**) unprocessed berberine; and nanoparticles prepared by (**B**) anti-solvent precipitation with a syringe pump (APSP), and (**C**) evaporative precipitation of nanosuspension (EPN).

Abbreviations: % T, percentage transmission; MB, material berberine; MB EPN, berberine nanoparticles prepared by EPN method; MB APSP, berberine nanoparticles prepared by APSP method.

clearly shows that unprocessed BBR dissolution was very low (<30%) in distilled water, 0.1 M HCl, and in PBS (pH 6.8), but NPs prepared by APSP and EPN methods showed an improved dissolution rate compared to that of raw BBR over the same time range (120 minutes). NPs made by both methods showed more than 70% dissolution within 15 minutes in all three dissolution media, which clearly indicates an enhanced dissolution rate. The enhanced dissolution rate of NPs can be ascribed to certain factors such as increased surface area, conversion to amorphous form or reduction in the crystallinity, good dispersibility, decrease in agglomeration and aggregation between the hydrophobic drug particles.[45]

NPs prepared by the EPN method showed a superior dissolution rate compared to those prepared by the APSP method.

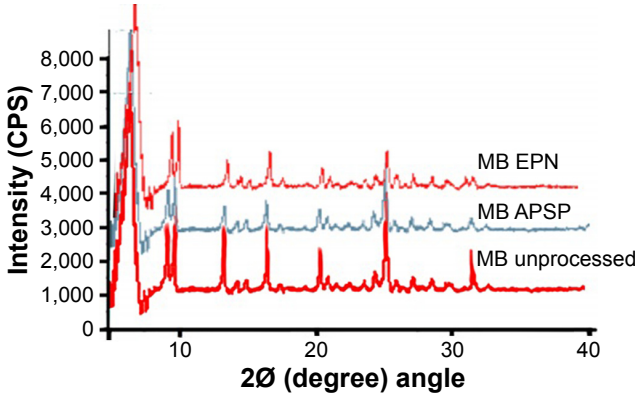

Figure 5 X-ray diffractograms of unprocessed berberine and nanoparticles prepared by anti-solvent precipitation with a syringe pump (APSP), and evaporative precipitation of nanosuspension (EPN).
Abbreviations: MB, material berberine; MB EPN, berberine nanoparticles prepared by EPN method; MB APSP, berberine nanoparticles prepared by APSP method.

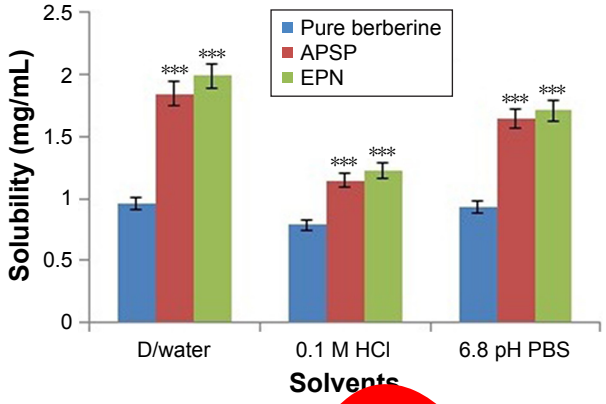

Figure 7 Solubility studies of unprocessed berberine and nanoparticles prepared by anti-solvent precipitation with a syringe pump (APSP) and evaporative precipitation of nanosuspension (EPN) methods.
Notes: ***$P<0.001$ as compared to unprocessed berberine. One-way ANOVA was used, followed by post-hoc Dunnett's test.
Abbreviations: ANOVA, analysis of variance; D/water, distilled water.

Antimicrobial assays

BBR NPs prepared by APSP and EPN methods had better antibacterial and antifungal activities than BBR (unprocessed) and respective standard antimicrobial drugs (Table 1). The antibacterial activity of BBR NPs produced by the EPN method was increased by three- to four-fold against Gram-positive bacteria. However, BBR NPs prepared by the APSP method showed a two- to three-fold increase in activity against Gram-positive bacteria as shown by a reduction in MICs given in Table 1. The results indicate a significant increase in antibacterial activity of BBR NPs as compared to unprocessed BBR. BBR NPs prepared by the EPN method were found to be more effective than miconazole, ie, BBR had a MIC value of 64 µg/mL against *C. glabrata* while the MIC of miconazole was 128 µg/mL.

Infections caused by pathogens such as *P. aeruginosa*, *S. aureus*, *E. coli*, and *C. albicans* have a high global prevalence, incidence rates, and very significant clinical implications, especially in developing countries like Pakistan. Factors involved in the increasing incidence rates include

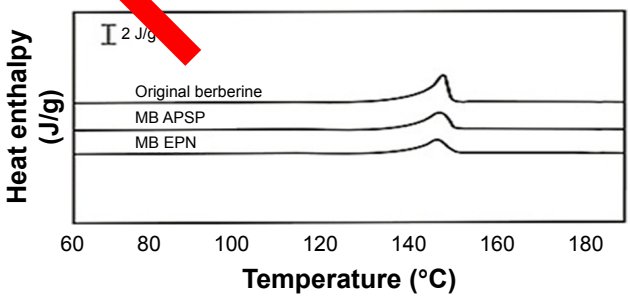

Figure 6 Differential scanning calorimetry results of unprocessed berberine (original berberine) and nanoparticles prepared through anti-solvent precipitation with a syringe pump (APSP) and evaporative precipitation of nanosuspension (EPN).
Abbreviation: MB, material berberine.

insufficient supply of antimicrobials, patient compliance issues, and self-medication, especially in poorer countries, and occurrence of antibiotic resistance. Plants and their derivatives, considered to be natural remedies, have thus been increasingly used not only in developing and poorer countries but also in developed countries, in which herbal medicines are currently gaining popularity. This use is not confined to a single domain but includes treatment of all ailments including infections caused by microorganisms.[50]

BBR has been demonstrated to reduce the infectivity of bacteria, fungi, and protozoa in both animals and humans.[50–53] Previous studies have shown that BBR has negligible activity against Gram-positive bacteria,[50] with Zhang et al[40] reporting the antibacterial activity of BBR against both Gram-positive and Gram-negative bacteria, with activities equal to or greater than 512 µg/mL against *S. aureus* and *E. coli*, respectively. In the present study, BBR NPs prepared by APSP and EPN methods have MIC values of 128 and 64 µg/mL respectively, which indicates a substantial (300%–400%) increase in antibacterial activity against Gram-positive bacteria. Similarly, a profound increase in antibacterial activity by BBR NPs prepared by the EPN method was found against *E. coli*, ie, MIC 32 µg/mL. The anticandidal activity of BBR NPs was shown to be better than unprocessed BBR. Against *C. albicans* and *C. glabrata*, the activity was measured as 64, 128, and 256 µg/mL, respectively, for NPs prepared by the EPN method, NPs prepared by the APSP method, and unprocessed BBR.

Conclusion

The dissolution of NPs prepared by EPN and APSP methods in aqueous medium were 76.8% and 74.1%, respectively, while

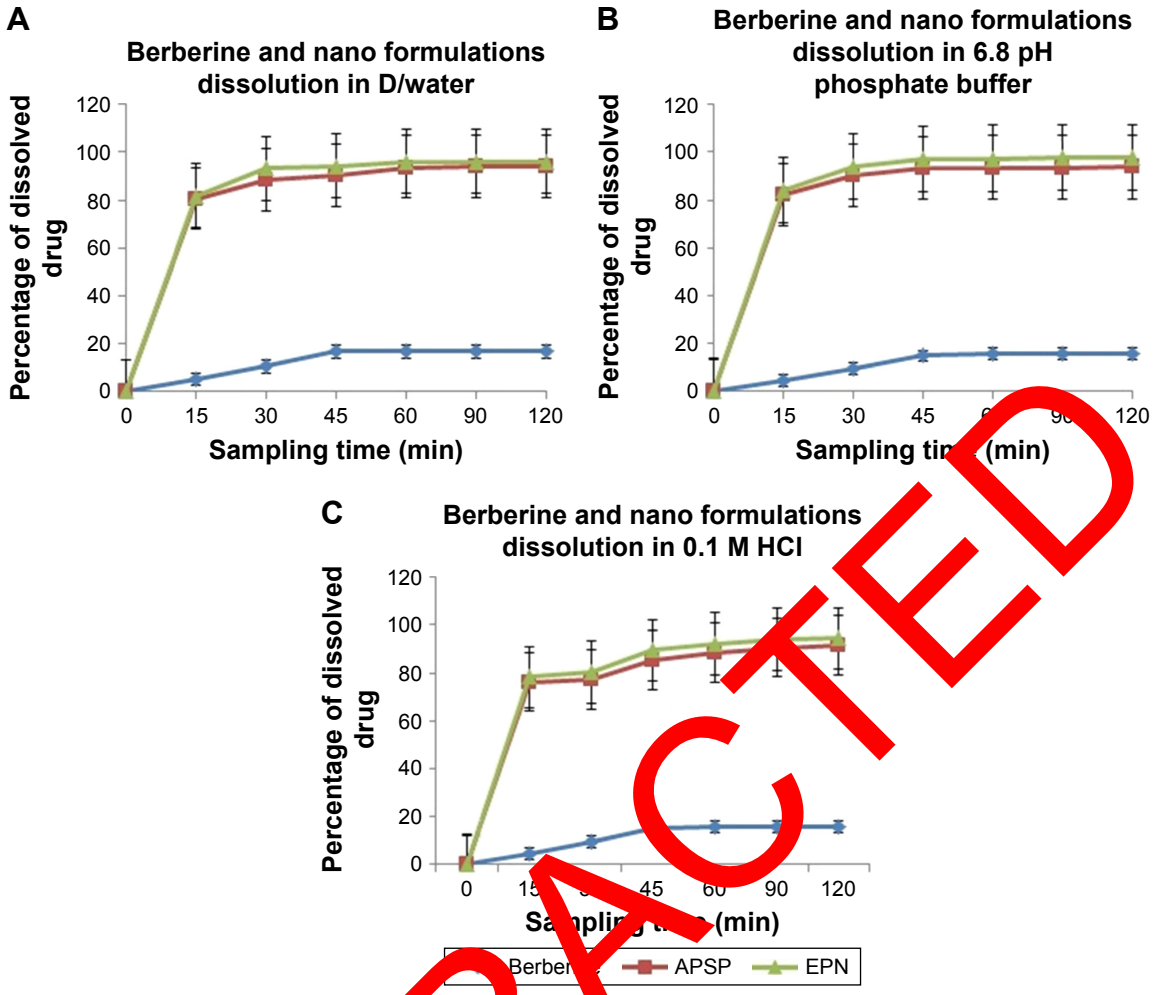

Figure 8 In vitro dissolution profiles of unprocessed berberine and nanoparticles prepared through anti-solvent precipitation with a syringe pump (APSP) and evaporative precipitation of nanosuspension (EPN) methods in (**A**) distilled water, (**B**) PBS pH 6.8, and (**C**) 0.1 M HCl.
Abbreviation: D/water, distilled water.

the solubilities were 1.992 mg/mL and 1.[illegible]7 mg/mL, respectively. Thus, NPs prepared by the EPN method showed better results than those prepared by the APSP method in terms of solubility and dissolution rate. Moreover, enhanced solubility and dissolution rate in turn increase the bioavailability of the respective NPs. BBR NPs produced by both APSP and EPN methods have shown promising activities against Gram-positive and Gram-negative bacteria, and yeasts, with NPs prepared by the EPN method showing superior results compared to those made with the APSP method, and the unprocessed drug.

Table 1 In vitro antibacterial and antifungal activities of berberine and its nanoparticles (NPs) prepared by anti-solvent precipitation with a syringe pump (APSP) and evaporative precipitation of nanosuspension (EPN) methods

	Gram-positive bacteria		Gram-negative bacteria		Yeasts	
	S. aureus	*B. subtilis*	*E. coli*	*P. aeruginosa*	*C. albicans*	*C. glabrata*
Berberine	512	>512	512	256	256	256
Berberine NPs by APSP	128	256	64	128	128	128
Berberine NPs by EPN	64	128	32	64	64	64
Norfloxacin	–	–	16	8	–	–
Clarithromycin	8	4	–	–	–	–
Miconazole	–	–	–	–	32	128

Note: Minimum inhibitory concentration values shown as μg/mL.
Abbreviations: *S. aureus, Staphylococcus aureus; B. subtilis, Bacillus subtilis; E. coli, Escherichia coli; P. aeruginosa, Pseudomonas aeruginosa; C. albicans, Candida albicans; C. glabrata, Candida glabrata.*

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Author contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest in this work.

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