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DEVELOPMENT, CHARACTERIZATION, AND *IN-VITRO* DRUG RELEASE EVALUATION OF *ARGEMONE MEXICANA* EXTRACT-LOADED SODIUM ALGINATE FILMS FOR BURN WOUND MANAGEMENT

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ABSTRACT

Introduction: Burn wounds require dressings that provide a moist environment, absorb wound exudates, and enable sustained delivery of therapeutic agents. This study aimed to develop and characterize sodium alginate-based polymeric films containing *Argemone mexicana* Linn. extract for potential burn wound management. **Materials and Methods:** *A. mexicana* leaves were authenticated, successively extracted, and incorporated into sodium alginate films by solvent casting using glycerine as a plasticizer. Two formulations (F1 and F2), selected through Box–Behnken Design optimization, were evaluated for surface pH, porosity, folding endurance, water absorption, water vapor transmission rate (WVTR), and in vitro drug diffusion using a Franz diffusion cell. **Results:** Both formulations produced uniform and flexible films with skin-compatible surface pH (5.5–5.8). The optimized formulation (F2) exhibited significantly higher porosity (42.1 ± 0.8%), water absorption (228.7 ± 3.5%), and WVTR (1932 ± 18 g/m²/day) than F1 ($p < 0.0001$). Although folding endurance decreased slightly after extract incorporation, all films retained satisfactory mechanical strength (>300 folds). In vitro diffusion demonstrated sustained release over 24 h, with F2 achieving approximately 99% cumulative drug release. **Discussion:** The improved porosity, moisture permeability, and exudate absorption of F2 can be attributed to the optimized sodium alginate–glycerine matrix, which facilitated efficient moisture management and controlled diffusion of phytoconstituents. These properties are desirable for maintaining an optimal wound-healing environment. **Conclusion:** The optimized *Argemone mexicana*-loaded sodium alginate film demonstrated excellent physicochemical characteristics and sustained drug release, suggesting its potential as a promising herbal wound dressing for burn wound management. Further in vivo and clinical investigations are warranted.

KEYWORDS: *Argemone mexicana*, sodium alginate, polymeric film, burn wound dressing, WVTR, drug diffusion.

1. INTRODUCTION

Burn injuries represent one of the most challenging forms of skin trauma, often resulting in prolonged inflammation, excessive exudate production, microbial infection, and delayed tissue regeneration.[1,2] An ideal burn wound dressing should maintain a moist wound environment, absorb excess exudates, permit adequate oxygen permeability, protect the wound from microbial contamination, and provide sustained release of therapeutic agents to accelerate the healing process.[3,4] Conventional dressings primarily serve as protective barriers and often require frequent replacement, which may cause pain, secondary infection, and delayed wound repair.[5] Consequently, there is growing interest in developing bioactive wound dressings based on natural polymers and medicinal plants that can actively promote tissue regeneration while minimizing adverse effects.[6]

Among naturally occurring polymers, sodium alginate has gained considerable attention as a wound dressing material because of its excellent biocompatibility, biodegradability, non-toxicity, high water absorption capacity, gel-forming ability, and favourable water vapour transmission characteristics.[7] Alginate-based films readily absorb wound exudates while maintaining a moist environment that facilitates cell migration, angiogenesis, collagen deposition, and re-epithelialization.[8] Moreover, sodium alginate serves as an effective carrier for controlled delivery of bioactive compounds, making it an attractive platform for herbal wound dressing development.[9]

Argemone mexicana Linn. (Family: Papaveraceae) is a medicinal plant widely used in traditional medicine for the treatment of wounds, burns, skin infections, ulcers, and inflammatory disorders.[10] The plant is rich in pharmacologically active alkaloids, flavonoids, phenolic compounds, tannins, and terpenoids, which have been reported to possess antioxidant, antimicrobial, anti-inflammatory, and tissue regenerative properties.[11] These phytoconstituents can modulate different phases of wound healing by reducing oxidative stress, inhibiting microbial growth, suppressing inflammatory mediators, and promoting fibroblast proliferation and collagen synthesis.[12] Despite its extensive traditional use and well-documented pharmacological potential, the application of *A. mexicana* in advanced polymeric wound dressing systems has received limited scientific attention.

Recent studies have focused predominantly on hydrogels, electrospun nanofibers, and composite dressings containing various medicinal plant extracts, whereas the formulation and optimization of *A. mexicana*-loaded sodium alginate films remain largely unexplored. Furthermore, comprehensive evaluation of physicochemical characteristics such as porosity, water absorption, water vapour transmission rate (WVTR), mechanical flexibility, and controlled drug release is essential to establish the suitability of such films for burn wound management.[13] Optimizing these parameters ensures efficient exudate management, adequate oxygen exchange, structural integrity, and sustained delivery of phytoconstituents at the wound site.

Therefore, the present study aimed to develop and optimize sodium alginate-based polymeric films incorporating ethanolic extract of *Argemone mexicana* using a Box–Behnken Design (BBD). The prepared films were systematically characterized for their physicochemical properties, including surface pH, porosity, water absorption, WVTR, thickness, folding endurance, and in vitro drug diffusion. The novelty of this study lies in the development of a statistically optimized herbal polymeric film combining the therapeutic potential of *A. mexicana* with the excellent film-forming properties of sodium alginate to produce a bioactive dressing with improved moisture management and sustained release characteristics for burn wound management. The findings of this study provide a scientific basis for the future

development of plant-based advanced wound dressings and offer a promising alternative to conventional topical burn therapies.

2. MATERIAL AND METHOD

2.1. Drugs, chemicals and equipment

Sodium alginate was procured from Loba Chem Pvt. Ltd. Glycerin, Petroleum Ether, Chloroform, Ethyl Acetate, and Ethanol were of analytical grade and used without further purification. All experiments were conducted at Narayan Institute of Pharmacy, Gopal Narayan Singh University, Jamuhar, Sasaram, Bihar.

2.2. Collection, Identification, and Authentication of Plant Material

Fresh leaves of *Argemone mexicana* Linn. (Family: Papaveraceae) were collected from the Jamuhar region of Sasaram, Bihar, India, during August 2024. Healthy, disease-free plants were selected to ensure the quality and consistency of the plant material. The collected specimens were cleaned to remove adhering soil and foreign matter prior to further processing. The plant was taxonomically identified and authenticated by Prof. N. K. Dubey, Professor, Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University (BHU), Varanasi, Uttar Pradesh, India, based on standard macroscopic and taxonomic characteristics. A voucher specimen was prepared, deposited in the departmental herbarium for future reference, and assigned the voucher specimen number *Papavera 2024/01*.

2.3. Preparation of Plant Material and Extraction

The collected leaves were thoroughly washed with running tap water followed by distilled water to remove dust and other impurities. The cleaned leaves were shade-dried at ambient temperature (25 ± 2°C) for approximately 15 days until a constant weight was obtained to preserve thermolabile phytoconstituents. The dried material was pulverized using a mechanical grinder and passed through sieve No. 40 to obtain a coarse and uniform powder. The powdered material was stored in airtight containers protected from moisture until extraction. Successive solvent extraction was carried out using a Soxhlet apparatus with solvents of increasing polarity, namely petroleum ether, ethyl acetate, chloroform, ethanol, and distilled water. Approximately 50 g of powdered plant material was extracted successively using 250 mL of each solvent under the extraction conditions presented in Table 1. After completion of each extraction cycle, the solvent was removed under reduced pressure using a rotary evaporator, and the concentrated extracts were stored in airtight containers at 4°C until further analysis and formulation.

Table 1: Extraction Conditions for Successive Solvent Extraction.

Solvent	Volume (mL)	Temperature (°C)	Extraction Time (min)
Petroleum ether	250	45	30
Ethyl acetate	250	75	45
Chloroform	250	60	60
Ethanol	250	80	90
Distilled water	250	100	180

2.4. Preliminary Phytochemical Screening

The successive extracts obtained from different solvents were subjected to qualitative phytochemical screening to identify the presence of major classes of secondary metabolites. Standard phytochemical tests were performed for alkaloids, flavonoids, glycosides, tannins, phenolic compounds, saponins, steroids, and terpenoids according to established pharmacognostic procedures. The ethanolic extract, which exhibited the richest phytochemical profile, was selected for subsequent formulation studies.

2.5. Preparation of *Argemone mexicana*-Loaded Polymeric Film

Polymeric films containing ethanolic extract of *Argemone mexicana* were prepared using the solvent casting technique.

Briefly, 25 mL of distilled water was transferred into a 50 mL beaker and stirred continuously using a magnetic stirrer at room temperature. Accurately weighed sodium alginate was gradually added under continuous stirring to avoid lump formation and to obtain a homogeneous polymeric solution. The dispersion was stirred for approximately 3 h until complete hydration and uniform dissolution of the polymer.

Glycerine was subsequently incorporated as a plasticizer and stirring was continued for an additional 15 min to ensure uniform distribution within the polymer matrix. Thereafter, the required quantity of ethanolic extract of *A. mexicana* was slowly added to the polymeric solution under continuous stirring for 1 h, producing a homogeneous drug-loaded casting solution (Table 2). The resulting viscous solution was carefully poured into clean, leveled Petri dishes and dried in a hot-air oven at 45 ± 2°C for 5 h. After complete drying, the films were gently peeled from the Petri dishes and stored in a desiccator containing silica gel until further physicochemical characterization and *in vitro* drug diffusion studies.

Table 2: Composition of the prepared formulations.

Formulation	Sodium Alginate (g)	Glycerine (g)	*A. mexicana* Extract (g)	Mixing Time (hr)	Drying Time (hr)
F1	1	0.25	6.25	4	5
F2	0.5	0.375	6.25	4	5

2.6. Characterization of *A. mexicana* extract loaded sodium alginate films

a. pH

The films were immersed in normal saline solution until equilibrium was reached. The pH of the solution was measured using a calibrated digital pH meter to determine compatibility with skin environment.[14]

b. Water Uptake

The swelling behavior of the films was evaluated by placing pre-weighed film samples (1 × 1 cm²) on phosphate buffer (pH 7.4). After 2 hours, the films were removed and weighed. The swelling index was calculated using the equation:[15]

$$WU = \frac{W_i - W_f}{W_i} * 100$$

Where WU is the water uptake, W_i is the Initial Weight and W_f is the Final Weight

c. Water Vapor transmission study

Water vapor transmission rate (WVTR) was determined gravimetrically according to the modified ASTM E96-95 standard method (16). Succinctly, a Film of a suitable dimension was mounted on circular opening of a vial containing 6 mL of distilled water. The vial was accurately weighed and placed in an incubator at 25℃. Then the vial was re-weighed periodically at 24, 48, and 72 h and then a rate of change in mass was plotted as function of time for each film. Finally, the WVTR was calculated using the equation as follows:

$$WVTR\ (gm^{-2}d^{-1}) = M * 24/TA$$

Where $WVTR$ the water is vapour transmission rate, M is the change in weight, T is time during which the change in weight occurred, and A is the exposed area of the film (m^2).

d. Porosity

A unit area of the film (1x1cm) was initially weighed and placed in the 5 mL of absolute ethanol solution in the test tube. The mouth of the test tube tightly closed by cotton to prevent the evaporation of alcohol. This was kept for 24h.

After 24h the final weight of the film was taken. If it's highly porous this indicates air-vapor transmission also increases that is ideal for wound healing at a faster rate.[17]

$$P = \frac{W_f - W_i}{V * D}$$

Where P is the Porosity, W_i is the initial weight, W_f is the final weight, V is the volume of sponge, D is the density of distilled alcohol.

e. Thickness Study

The major factor that greatly affects the functional properties of wound dressing materials is Thickness of the film. The thicknesses of the films were measured using a screw gauge by randomly selecting four positions on each film. The mean was used to express the thickness of the films. To ascertain the mass uniformity of each film, four pieces of equal sizes were cut from different positions of each film followed by weighing their respective masses with electronic balance and eventually, these values were used to calculate the average mass.[18]

f. Folding Endurance

A strip of the specific area 3cm × 3cm (9 cm^2) is to be cut evenly and repeatedly folded from both sides at the same place till it breaks. The number of the same place without breaking is calculated which gives information about the flexibility of the film.[19]

g. Drug Content Study

A unit area of the film (1x1 cm) was taken and dissolved in the suitable solvent with the help of magnetic stirrer. Then the sample was taken and filtered. The filtrate sample was subjected to check absorbance by the help of UV Spectrophotometer at their respective wavelengths against a blank solution which was prepared by the same protocol but not containing drug and to determine the drug content of the film of that unit area. These studies provide to know that how much amount of drug present in 1 cm^2 of the film.[9]

h. Diffusion Study

Franz diffusion cell was used to determine the drug release profile of Nicotinamide loaded sodium alginate film. A unit area of the film was placed between the donor component and the receptor component in the Franz diffusion chamber.

The receptor component was filled with water and it was kept at 37°C by circulating through an external thermostatic water bath (Fig. 2). After 30 mins interval from the receptor chamber, the drug solution was withdrawn, and simultaneously the water introduced to keep the receptor solution constant during the experiment. Then the absorbance of the withdrawn solution was checked. This testing determines how much amount of an active ingredient must permeate to provide a clinical effect at each time point (20,21).

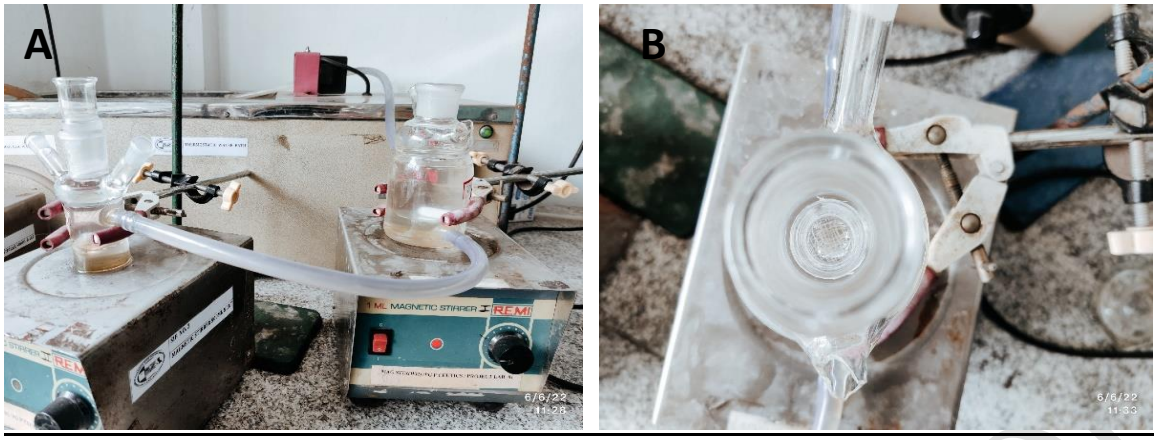

Figure 1: Franz diffusion cell used to determine the drug release profile of A. *mexicana* extract loaded sodium alginate film. A. Complete Franz diffusion cell assembly, B. upper view of Franz diffusion cell loaded with film.

3. RESULTS & DISCUSSION

3.1. Physical Appearance of the Polymeric Films

The solvent casting technique successfully produced flexible, smooth, homogeneous, and translucent sodium alginate films loaded with *Argemone mexicana* extract. The prepared films were easily peeled from the Petri dishes without visible cracks, air bubbles, or phase separation (Figure 1). Incorporation of the ethanolic extract imparted a characteristic greenish-brown color to the films due to the presence of chlorophyll and phytoconstituents, while the addition of glycerine improved film flexibility and prevented brittleness. Both formulations (F1 and F2) maintained sufficient structural integrity during handling, indicating that sodium alginate formed a stable polymeric matrix capable of uniformly entrapping the plant extract.

Fig. 2: Prepared film of ethanolic extract of *A. mexicana.*

3.2. Surface pH

The surface pH of wound dressings plays a vital role in preventing skin irritation and maintaining an environment favorable for wound healing. As shown in Figure 2, the surface pH of the blank film, F1, and F2 ranged between 5.5 and 5.8, which closely corresponds to the physiological pH of healthy human skin. The blank film exhibited a surface pH of 5.50 ± 0.04, whereas incorporation of *Argemone mexicana* extract slightly increased the pH to 5.62 ± 0.03 for F1 and 5.79 ± 0.05 for F2. Statistical analysis demonstrated a significant difference among the formulations ($p < 0.0001$). However, all values remained within the acceptable dermatological range, suggesting that the films are unlikely to cause irritation upon topical application. The slight increase in pH following extract incorporation may be attributed to

naturally occurring alkaloids and phenolic constituents present in the ethanolic extract. Nevertheless, the optimized formulation maintained a mildly acidic environment that may suppress bacterial proliferation while supporting fibroblast activity and epithelial regeneration.

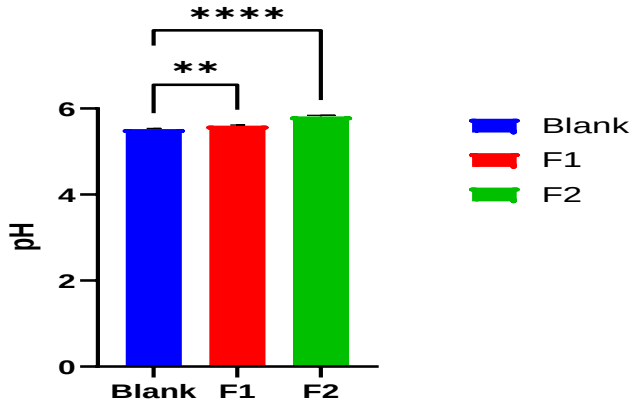

Fig. 3: Surface pH of the formulations. Data are expressed as mean ± SD (n = 3). Statistical significance was determined by one-way ANOVA followed by Tukey's multiple comparison test (p < 0.01; ****p < 0.0001).**

3.3. Water Uptake

Water absorption capacity determines the ability of wound dressings to absorb wound exudates while maintaining a moist healing environment. As presented in Figure 3, the blank film exhibited the lowest water absorption (168.4 ± 2.8%), whereas F1 and F2 demonstrated values of 204.3 ± 3.2% and 228.7 ± 3.5%, respectively. The enhanced water uptake observed for F2 may be explained by its higher porosity and increased hydrophilic nature resulting from the optimized polymer-plasticizer composition. Sodium alginate contains abundant carboxyl and hydroxyl groups capable of forming hydrogen bonds with water molecules, thereby promoting rapid swelling. Efficient water absorption is particularly beneficial for burn wounds because excessive wound exudates may delay healing and increase the risk of microbial infection. Therefore, the higher water uptake capacity of F2 indicates improved exudate management and maintenance of an optimal moist wound environment.

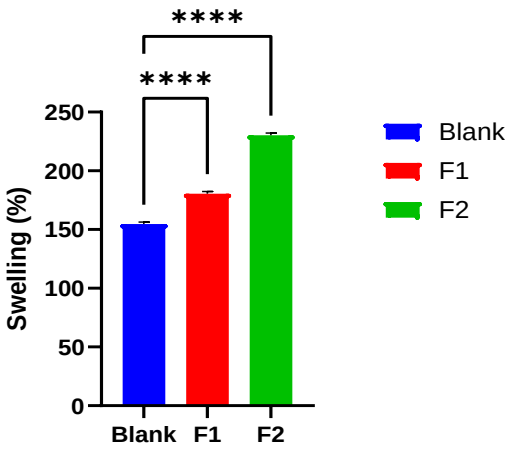

Fig. 4: Effect of formulation composition on the Water uptake rate of sodium alginate-based films containing *Argemone mexicana* extract. Data are expressed as mean ± SD (n = 3). Statistical significance: ****p < 0.0001.

3.4. Water Vapour Transmission Study

An appropriate WVTR is essential to maintain moisture balance within the wound bed. Excessively low WVTR may cause fluid accumulation and maceration, whereas excessively high WVTR can lead to wound dehydration. As shown in Figure 4, WVTR increased from 1654 ± 20 g/m²/day for the blank film to 1816 ± 16 g/m²/day for F1 and 1932 ± 18 g/m²/day for F2. The increase in WVTR is consistent with the observed enhancement in film porosity and hydrophilicity. The interconnected pore structure produced by the optimized formulation facilitated controlled transmission of water vapor while maintaining sufficient moisture within the wound. The WVTR values obtained for F2 fall within the range generally considered suitable for burn wound dressings, indicating its ability to maintain an optimal moist healing environment without causing excessive dehydration or fluid accumulation.

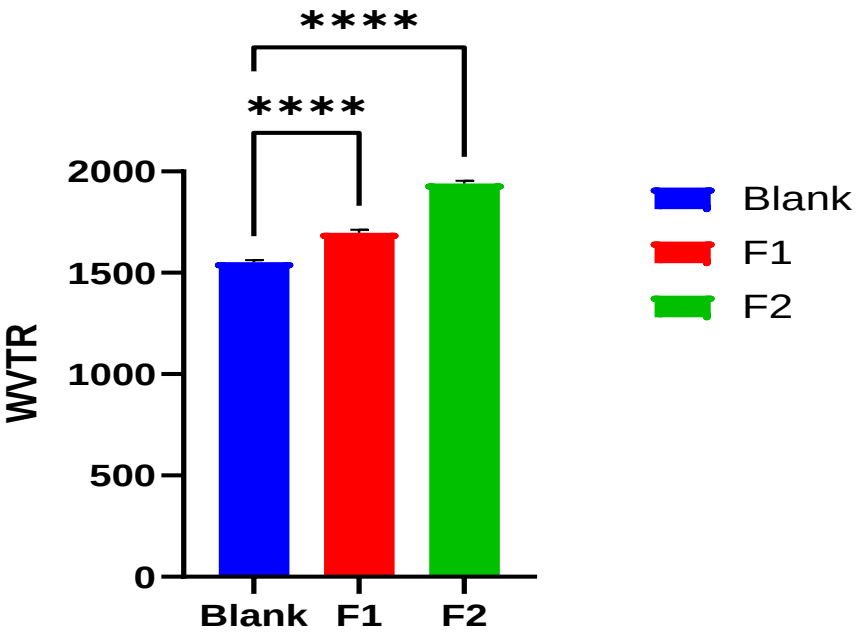

Fig. 5: Effect of formulation composition on the water vapor transmission rate (WVTR) of sodium alginate-based films containing *Argemone mexicana* extract. Data are expressed as mean ± SD (n = 3). Statistical significance: ****p < 0.0001.

3.5. Porosity

Porosity governs oxygen permeability, nutrient transport, moisture balance, and cellular infiltration within wound dressings. The porosity values shown in Figure 5 revealed a progressive increase following incorporation of the herbal extract. The blank film exhibited the lowest porosity (29.4 ± 0.5%), whereas F1 and F2 demonstrated porosity values of 36.8 ± 0.7% and 42.1 ± 0.8%, respectively. The significantly higher porosity of F2 ($p < 0.0001$) can be attributed to the optimized sodium alginate-to-glycerine ratio, which facilitated the formation of a more interconnected polymeric network during solvent evaporation. Increased glycerine concentration likely enhanced chain mobility, producing micro voids that improved fluid absorption and oxygen diffusion. Adequate porosity is advantageous for burn wound healing because it facilitates gaseous exchange while preventing excessive moisture accumulation, thereby creating a favourable environment for tissue regeneration.

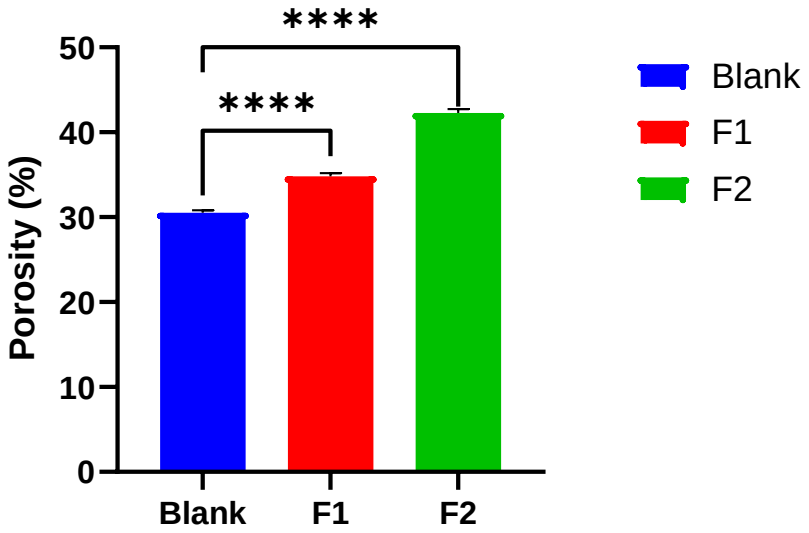

Fig. 6: Effect of formulation composition on the porosity of sodium alginate films containing *Argemone mexicana* extract. Values are expressed as mean ± SD (n = 3). ****p < 0.0001.

3.6. Thickness

The thicknesses of both the formulations were found 0.41 ± 0.90 and 0.44 ± 0.38. As per the result, the thickness of the film F2 having 0.42 ± 0.38 to 0.44 ± 0.28 respectively which is more than other non-crosslinked films (F1). This indicates that the formulations have small variations in thickness with the change in the amount of the excipients (table 3).

3.7. Folding Endurance

Mechanical flexibility is an important requirement for wound dressing materials because the dressing must withstand repeated bending during application without cracking. As illustrated in Table 3, the blank sodium alginate film exhibited the highest folding endurance (402 ± 5 folds), reflecting the excellent flexibility of the polymeric matrix.

Incorporation of *Argemone mexicana* extract slightly reduced folding endurance to 356 ± 4 folds (F1) and 328 ± 6 folds (F2). Although a statistically significant reduction ($p < 0.0001$) was observed, both formulations retained folding endurance values exceeding 300 folds, indicating adequate flexibility for clinical handling. The reduction may be attributed to increased intermolecular interactions between sodium alginate chains and phytoconstituents, producing a comparatively rigid polymer network. Nevertheless, the optimized formulation maintained sufficient mechanical integrity for wound dressing applications.

Table 3: Physicochemical characteristics of sodium alginate films loaded with *Argemone mexicana* extract (Mean ± SD, n = 3).

Formulation	Surface pH	Water Uptake (%)	WVTR (g/m²/day)	Porosity (%)	Thickness (mm)	Folding Endurance (times)
Blank	5.52 ± 0.02	154.63 ± 1.80	1552.33 ± 9.61	30.50 ± 0.30	0.40 ± 0.01*	323.67 ± 2.52
F1	5.60 ± 0.02	180.43 ± 1.90	1698.33 ± 13.50	34.83 ± 0.35	0.41 ± 0.01*	305.67 ± 5.03
F2	5.82 ± 0.03	230.33 ± 1.80	1940.33 ± 13.05	42.27 ± 0.45	0.42 ± 0.01*	308.67 ± 3.06

3.8. Diffusion study

The cumulative drug diffusion profiles of F1 and F2 are presented in Figure 6. Both formulations demonstrated sustained release of phytoconstituents over a period of 24 h, confirming the suitability of sodium alginate as a controlled-release polymeric matrix. F1 exhibited approximately 92% cumulative drug release, whereas the optimized formulation F2 achieved nearly 99% cumulative release after 24 h. An initial burst release was observed during the early diffusion period, followed by a gradual and sustained release phase. The improved release behavior of F2 can be attributed to its optimized polymer concentration, higher porosity, enhanced swelling characteristics, and increased water uptake, which facilitated penetration of the dissolution medium into the polymer matrix and accelerated diffusion of phytoconstituents. Sustained drug release is advantageous for burn wound management because it prolongs therapeutic exposure at the wound site, reduces the frequency of dressing replacement, and maintains continuous antimicrobial and antioxidant activity throughout the healing process.

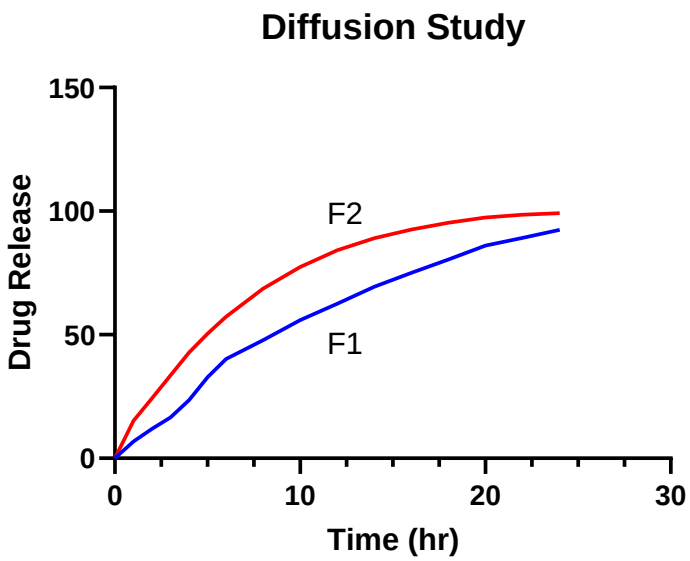

Fig. 7: *In-vitro* drug diffusion profiles of formulations F1 and F2 over 24 h determined using a Franz diffusion cell.

3.9. Kinetic Modeling of Diffusion Data

The *in-vitro* drug release data of the selected formulations F1 and F2 were subjected to kinetic modeling to elucidate the mechanism of drug release from the sodium alginate films. The release profiles were fitted to various mathematical models, including zero-order, first-order, Higuchi, Hixson–Crowell, and Korsmeyer–Peppas models. The correlation coefficient (R^2) values obtained from these models were used to determine the best-fit release kinetics.

Among the investigated models, the Higuchi model exhibited the highest correlation coefficients for both formulations, with R^2 values of 0.9775 for F1 and 0.9726 for F2, indicating that the release of nicotinamide predominantly follows a diffusion-controlled mechanism. The high goodness-of-fit to the Higuchi equation suggests that drug diffusion through the hydrated polymeric matrix is the principal factor governing the release process. In comparison, the zero-order (F1: 0.9602; F2: 0.8673), first-order (F1: 0.6373; F2: 0.4737), and Hixson–Crowell (F1: 0.9602; F2: 0.8673) models showed comparatively lower correlation coefficients, indicating that the release is not primarily governed by constant-rate kinetics, concentration-dependent dissolution, or changes in surface area of the dosage form.

Further characterization using the Korsmeyer–Peppas model yielded correlation coefficients of 0.8656 and 0.7066 for F1 and F2, respectively. The release exponent (n) values were 1.0716 for F1 and 0.9290 for F2. Since both n values are greater than 0.89, the drug release mechanism can be classified as Super Case-II transport, indicating that polymer chain relaxation and erosion contribute significantly to drug release along with diffusion. This behaviour is characteristic of hydrophilic polymeric matrices such as sodium alginate, where swelling of the polymer, relaxation of the polymer chains, and gradual matrix erosion collectively regulate the release of the incorporated drug.[22]

The kinetic analysis demonstrates that although diffusion through the hydrated matrix plays a major role, the release of *A. mexicana* extract from both F1 and F2 films is also influenced by polymer relaxation and structural reorganization. These findings confirm that the developed sodium alginate films provide controlled drug release through a combination of diffusion and polymer relaxation mechanisms, making them suitable for sustained topical drug delivery applications.[23]

Table 4: Kinetic modelling of diffusion Study.

Batch No.	F1 (r^2)	F2 (r^2)	n Value	
			F1	F2
Zero order	0.9602	0.8673	–	
First order	0.6373	0.4737		
Higuchi model	0.9775	0.9726		
Hixson Crowell	0.9602	0.8673		
Kors-Meyer Peppas model	0.8656	0.7066	1.0716	0.929

CONCLUSION

The present study successfully developed and optimized *Argemone mexicana* extract-loaded sodium alginate polymeric films for potential application in burn wound management using a Box–Behnken Design (BBD) approach. The optimized formulation (F2) exhibited excellent physicochemical characteristics, including a skin-compatible surface pH, high water absorption capacity, appropriate water vapor transmission rate, improved porosity, uniform thickness, and satisfactory mechanical flexibility, all of which are desirable attributes for an ideal wound dressing. These properties collectively ensure efficient exudate management, adequate gaseous exchange, maintenance of a moist wound environment, and structural integrity during application.

The *in-vitro* diffusion study demonstrated sustained release of the incorporated phytoconstituents over 24 h, while kinetic modeling revealed that drug release predominantly followed the Higuchi diffusion model, indicating diffusion-controlled release through the hydrated sodium alginate matrix. Furthermore, the Korsmeyer–Peppas model suggested a Super Case-II transport mechanism, confirming that polymer relaxation and matrix erosion, in addition to diffusion, contributed to the release behavior. Such controlled release is advantageous for maintaining prolonged therapeutic concentrations at the wound site while reducing the frequency of dressing replacement.[24]

The integration of the antioxidant, anti-inflammatory, and antimicrobial phytoconstituents of *A. mexicana* with the excellent film-forming and biocompatible properties of sodium alginate resulted in a bioactive polymeric dressing capable of addressing several critical requirements of burn wound care. The statistical optimization further demonstrated that an appropriate balance between polymer and plasticizer concentrations can significantly enhance the functional performance of the developed films.[25,26]

Overall, the findings provide strong experimental evidence that the optimized *Argemone mexicana*-loaded sodium alginate film represents a promising, economical, and plant-based wound dressing with considerable potential for burn wound management. Although the present work establishes its physicochemical suitability and controlled-release characteristics, further investigations involving antimicrobial efficacy, cytocompatibility, *in vivo* burn wound healing studies, histopathological evaluation, and clinical validation are required before translation into clinical practice. These future studies will further establish the therapeutic potential of this herbal polymeric film as a safe and effective alternative to conventional burn wound dressings.

AUTHORS' CONTRIBUTIONS

Omsatyam: Writing Original draft, Shashi Ranjan Singh & Laliteshwar Pratap Singh: Reviewing & Editing draft, Dharmendra Kumar: Supervision

FUNDING: None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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LIST OF ABBREVIATIONS

A. mexicana	:	*Argemone mexicana* Linn.
ASTM	:	American Society for Testing and Materials
BBD	:	Box–Behnken Design
cm	:	Centimeter
cm²	:	Square Centimeter
°C	:	Degree Celsius
F1	:	Formulation 1
F2	:	Formulation 2
g	:	Gram
mg	:	Milligram
mL	:	Milliliter
min	:	Minute
mm	:	Millimeter
n	:	Release Exponent (Korsmeyer–Peppas Model)
pH	:	Potential of Hydrogen
R^2 (r^2)	:	Correlation Coefficient
SD	:	Standard Deviation
UV–Vis	:	Ultraviolet–Visible Spectroscopy
w/v	:	Weight per Volume
WVTR	:	Water Vapor Transmission Rate

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