RESEARCH PAPER

DEVELOPMENT AND EVALUATION OF SUMATRIPTAN LOADED TRANSDERMAL FILMS USING BIOPOLYMERIC FUNCTIONAL AGENT

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ABSTRACT

A large number of people around the world suffer from migraine, a neurological illness that often brings on intense, one-sided throbbing headaches together with queasiness, vomiting, and a strong aversion to light and noise. Since this condition is among the top contributors to disability globally, it severely interferes with everyday routines, cuts down work efficiency, and puts considerable strain on medical services. Sumatriptan, the first medication introduced in the triptan family, is commonly used to halt migraine episodes early by targeting serotonin 5-HT1B/1D receptors, an action that constricts expanded blood vessels inside the skull and blocks the release of inflammatory neuropeptides from trigeminal nerve endings. Despite its effectiveness, oral delivery of sumatriptan comes with significant downsides: roughly three out of four drugs taken by mouth do not work as intended, and during a migraine, delayed stomach emptying and nausea make absorption even more unreliable. Transdermal patches present a promising solution. These thin, bendable polymer sheets send medication across the skin at a steady pace, avoiding the digestive tract and the liver's first-pass effect. How well they function depends on the drug's physical and chemical traits, the polymer matrix, added plasticizers, and the way the formulation interacts with the skin's outer barrier (stratum corneum). In recent years, natural and semi-synthetic biopolymers have attracted interest because they are safe for living tissue, break down naturally, and can easily

form stable films. For this project, a new biopolymer taken from *Oryza sativa* L. poha (flattened rice) served as a matrix-building agent to create transdermal patches containing sumatriptan. The thinking behind this approach was to test a natural, inexpensive, and easy-to-use system that would improve how sumatriptan is delivered while fixing the shortcomings of standard oral forms. The study set out to prepare, assess, and refine these patches so they would provide controlled drug release, adequate mechanical strength, and proper physical properties for treating migraines. Initial experiments included checking the drug's appearance and smell, measuring its melting point (recorded as 170.64°C), running UV spectroscopy (peak absorbance at 227 nm), plus FTIR and DSC analyses, all of which confirmed that the drug and excipients got along well without unwanted interactions. The patches were made using a solvent evaporation method, and five different batches (F1 through F5) were examined for thickness, weight consistency, folding endurance, tensile strength, moisture pickup, moisture loss, drug content, pH, and drug release in a lab setting. A modified diffusion cell with a cellulose acetate membrane kept at 32 ± 0.5°C was used for the release studies. Every patch turned out uniform, see-through, and pliable. The best-performing batch, labeled F4, showed a thickness of 0.26 mm, folding endurance above 300, tensile strength of 0.35 kg/cm², drug content of 99.87%, and a pH of 6.8. Over a six-hour period, F4 released 88.34% of its sumatriptan. When the release data were fitted to different mathematical models, the Higuchi model gave the closest match (R^2 = 0.9888), pointing to a diffusion-controlled release process, along with mixed zero-order (R^2 = 0.9255) and first-order (R^2 = 0.9761) behaviour. To sum up, the biopolymer derived from *Oryza sativa* L. poha turned out to be an effective, low-cost, and tissue-friendly film-forming material. Sumatriptan-loaded transdermal patches, especially formulation F4, offer a practical, needle-free alternative to oral medication for handling acute migraine attacks, though additional testing in living organisms is still needed.

Keywords: Sumatriptan; transdermal patches; Oryza sativa L. poha; biopolymer; migraine; sustained release; solvent casting; Higuchi kinetics; natural excipient; ease of use

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INTRODUCTION

Migraines are a frequent and disabling neurological condition. They typically involve repeated episodes of one-sided, throbbing head pain that ranges from moderate to severe. These attacks are often paired with symptoms like nausea, vomiting, and heightened sensitivity to light and sound. As a major contributor to global disability, migraines significantly affect daily functioning, well-being, and the demand for medical services.**[1]**

A common and debilitating issue within neurology is migraine. This disorder usually comes in the form of recurring attacks, each marked by throbbing pain on one side of the head that can be moderate to severe in intensity. Nausea, vomiting, and increased sensitivity to both light and noise frequently accompany the headache. Since migraines are one of the top causes of disability worldwide, they take a serious toll on a person's everyday life, ability to function, and the healthcare system.**[2]**

Sumatriptan is the original drug in the triptan family and remains one of the most commonly prescribed medications for stopping a migraine attack in its early stages. It works by selectively activating serotonin receptors known as 5-HT1B and 5-HT1D. This action causes blood vessels in the head to narrow and blocks the release of inflammatory neuropeptides from nerve endings in the trigeminal system. As a result, both the pain of a migraine and its accompanying symptoms are reduced.**[3]**

Transdermal films are thin, bendable sheets made from polymers that release medication through the skin at a steady pace. How well they work depends on several factors, including the drug's physical and chemical traits, the type of polymer matrix used, whether plasticizers are added, and how the film interacts with the skin's outer protective layer (the stratum corneum). Recently, biopolymers from natural or semi-synthetic sources have drawn interest for these applications due to their ability to break down naturally, their safety for living tissue, and their capacity to form stable films. **[4]**

For this research, a newly identified biopolymer extracted from Oryza sativa L. poha served as a functional matrix-forming agent in creating transdermal films loaded with sumatriptan. The idea behind this method was to investigate a natural, low-cost, and user-friendly delivery system that could enhance how sumatriptan is administered while addressing the limitations found in traditional drug forms. **[5]**

Accordingly, the goal of this work was to prepare, test, and fine-tune sumatriptan-loaded transdermal films using a biopolymer as a functional agent. The aim was to create a delivery

system that offers steady drug release, good mechanical integrity, and desirable physical properties, making it a viable candidate for further exploration in the treatment of migraine. **[6]**

MERITS OF TDDS	**BRIEF EXPLANATION**	**DEMERITS OF TDDS**	**BRIEF EXPLANATION**
Avoids first-pass metabolism	The drug enters systemic circulation without hepatic first-pass loss.	Limited to suitable drugs	Only drugs with low molecular weight, adequate lipophilicity, and good potency can pass through skin effectively.
Bypasses gastrointestinal tract	Useful when oral delivery is affected by nausea, vomiting, or gastric stasis.	Skin barrier limits absorption	The stratum corneum strongly restricts permeation.
Controlled and sustained release	Helps maintain more stable plasma concentration.	Limited drug loading	High-dose drugs are difficult to deliver through patches.
Improves patient compliance	Non-invasive and easy to use.	Local skin irritation	Redness, rash, and contact dermatitis may occur.
Useful during vomiting or swallowing difficulty	Especially helpful in acute migraine or in patients who cannot take oral medicines.	Adhesion problems	Patches may detach due to sweat, movement, or body hair.
Easy to stop therapy	Removing the patch stops further drug input quickly.	Variable absorption	Skin thickness, site, age, and hydration can affect drug delivery.
May reduce peak-related side effects	Lower peak plasma levels may reduce adverse effects.	Not ideal for emergencies	TDDS may not provide the very rapid onset needed for some acute conditions.

Table 1: Merits and Demerits of TDDS [7-9]

RESEARCH OBJECTIVE

Even though taking medication by mouth is the most common and preferred method, nearly three out of every four orally taken drugs fail to perform as expected in the body. Recognizing this drawback, the current study seeks to create a formulation that ensures a more controlled release of the drug. To achieve this, a transdermal delivery system has been proposed. Beyond improving drug performance, the ease with which such a system can be used also adds to its overall value.

The main objective of this study was to develop and evaluate sumatriptan-loaded transdermal films using a natural biopolymeric functional agent isolated from *Oryza sativa* L. poha.

The study aimed to design a safe, effective, non-invasive, patient-friendly drug delivery system that can by-pass gastrointestinal limitations and first-pass metabolism, thereby improving the therapeutic delivery of sumatriptan in migraine management.

METHODOLOGY

Procurement of Drugs and Excipients

The below mentioned substances of pharma grades as well as the best available Laboratory reagents that are being used supplied by the manufactures. Distilled water was used in all the performed experiments.

Table 2: List of material used

S. No	Material used	Supplier
1	Sumatriptan	Biodeal Pharmaceuticals Ltd, Solan (H.P), India
2	Oryza sativa L.	Extracted from poha
3	Sodium alginate	CDH, India
4	HPMC K4M	Koch light laboratories
5	PEG-400	CDH, India
6	Glycerine	CDH, India
7	Distilled water	In house
8	Dextrose	CDH, India
9	Sorbitol	CDH, India

Instrument used:

List of instruments being utilized throughout this study and their manufacturer have been listed underneath:
Table 3: List of Instrument

S. No	Instrument	Manufacturer
1	UV Visible Spectrophotometer	Shimadzu UV-1800
2	Infrared Spectrophotometer	Shimadzu FTIR Affinity
3	Mechanical stirrer	Remi instrument ltd.
4	Magnetic stirrer	Alcon
5	Electric weighing balance	Mettler toledo
6	Digital pH meter	Eutech & Oakton
7	Melting point apparatus	Labman Scientific instrument
8	Probe sonicator	Mangaldeep
9	Tapped density apparatus	Labindia
10	Hot air oven	Grover Enterprise
11	Distilled water apparatus	Borosil
12	Ultracentrifuge	Remi R-4c
13	Horizontal glass diffusion cell	Fabricated
14	Film thickness measuring instrument	Electro lab (vernier calliper)

Preformulation Studies:

Characterization of Sumatriptan

Organoleptic factors such as appearance, odour, texture, and colour were tested of the drug and compared to values/descriptions provided in the literature.

Melting Point

Melting temperature decision has been taken by presenting little amount of the drug powder into capillary tube 10-15cm long and about 1mm in diameter. The tube was sealed from one side by flame then putting them in electric melting temperature equipment and the

temperature range across at specimen starts melting was considered as melting point. **[10-11]**

UV Spectroscopy:

The UV Spectra of drug was taken at 200-400 nm and compared with that reported in the literature.

Determination of λmax and Calibration curve of Sumatriptan

Preparation of stock solution: 100mg of Sumatriptan weighed in and poured into the 100ml volumetric flask dispersed within 50 ml of pH 7.2 Phosphate buffer solution and subsequently the volume was made up to 100ml then the Stock solution becomes of concentration i.e., 1mg/ml.

Preparation of standard solution: 10ml of formed stock solution was taken and diluted up to 100ml with pH 7.2 Phosphate buffer to obtained standard solution of 100 µg/ml. The spectrum and calibration curve were plotted in the respective solution.

Preparation of working solution: From the standard solution, pipette out 2, 4, 6, 8, 10, 12, 14 and 16ml of solution and dilute them with pH 7.2 Phosphate buffer solution respectively. Absorbance of each one of the solutions was assessed spectrophotometrically in the range of 200-400nm to record the spectrum, λmax and standard curve of Sumatriptan in Phosphate buffer solutions respectively. **[12]**

Identification Tests.

Identification tests such as infra-red (IR) spectroscopy, differential scanning calorimetry (DSC) of isolated biopolymer were performed.

Fourier Transform Infra-red (FTIR) Spectroscopy

The FTIR is done to know the interaction among drug and excipients. Infrared spectrum of Sumatriptan and the optimized Sumatriptan using biopolymer transdermal formulation has been calculated on the FT-IR spectrophotometer by utilizing the KBr dispersion method. Potassium bromide was intended for adjustment of base line but then range of dried mixture of drug and KBr was operated and further drug with some other excipients in the wavelength region between 4000-400cm-^{1}. **[13]**

Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry Individual and physical mixture consisting of Sumatriptan and the polymers: Extracted biopolymer, HPMC K4M and Sodium alginate were scanned over a temperature range of 25-2500 C at the rate of 50/min using differential scanning colorimetry (DSC-60, Shimadzu, Japan).**[14]**

Preparation Of Transdermal Films

Formulation of placebo films

The purpose of this research was to determine the best polymer, plasticizer, and solvent system combination. A variety of transdermal films with these components in various ratios were created. Different placebo films (no use of drug) were developed in order to choose the best film for drug integration. Solvent evaporation process was used to create the transdermal film. Polymers, plasticizers, and a penetration enhancer were dissolved in 10 ml of water to form the film casting solution. The resulting uniform solution is poured in the Petri dish with the diameter of 7cm. The solvent was allowed to evaporate at room temperature. The films took approximately 48 hours to completely dry. After 48 hours, all of the dried films were hauled out and wrapped in aluminium foil before being kept in desiccators at room temperature.**[15]**

Table 4: Formulation of placebo films

Ingredient (mg/film)	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
HPMC K4M	50	50	50	50	50	50	100	100	100	100

Sodium alginate	100	100	100	200	200	200	100	100	100	200
Glycerine	1	-	-	1	-	-	1	-	-	1
PEG-400	-	1	-	-	1	-	-	1	-	-
Sorbitol	-	-	1	-	-	1	-	-	1	-
Water	10	10	10	10	10	10	10	10	10	10
Remark	++	++	-	-	-	-	+++	+++	++	++

Table 5: Formulation of placebo films

Ingredient (mg/film)	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**	**T21**	**T22**
HPMC K4M	100	100	150	150	150	150	150	150	-	-	-	-
Sodium alginate	200	200	100	100	100	200	200	200	200	300	450	600
Dextrose	-	-	-	-	-	-	-	-	100	100	150	200
Glycerine	-	-	1	-	-	1	-	-	-	-	-	-
PEG-400	1	-	-	1	-	-	1	-	0.8	0.8	0.8	0.8
Sorbitol	-	1	-	-	1	-	-	1	-	-	-	-
-Water	10	10	10	10	10	10	10	10	10	10	10	10
Remark	-	-	+++	+++	++	+++	+++	-	++	-	++	++

Ingredient (mg/film)	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**	**T31**	**T32**
EXTRACTED BIOPOLYMER	200	250	300	350	350	300	200	250	300	350
HPMC K4M	100	100	150	150	75	75	50	50	100	150
Sodium alginate	100	100	100	200	75	75	50	50	100	100
Glycerine	1	-	1	1	1	1	-	1.2	-	-
PEG-400	-	1	-	-	-	-	1.2	-	1.2	1.2

Water	10	10	10	10	10	10	10	10	10	10
Remark	++	-	++	+	+++	+++	-	++	+++	-

We have compared the HPMC K4M and Sodium alginate films with biopolymer films, and there are no significant physical changes. So, we have finally selected a biopolymer film of particular concentration to incorporate the drug.

Fabrication of Sumatriptan transdermal films

Solvent evaporation process was used to create the transdermal film. Polymer(biopolymer,) plasticizer (PEG 400), and a penetration enhancer, were dissolved in water to form the film casting solution. 96.16 mg of drug were dissolved in the 8ml of water and sonication for 10-15 minutes. The resulting uniform solution is poured in the petridish with the diameter of 7cm. The solvent was allowed to evaporate and kept at room temperature. The films took approximately 48 hours to completely dry. After 48 hours, all of the dried films were hauled out and wrapped in aluminium foil before being kept in desiccators at room temperature. As a result, the produced films adhered to the bandage's adhesive layer.**[16]**

Table 7: Formulation of transdermal films containing Sumatriptan

Ingredient (mg/film)	**F1**	**F2**	**F3**	**F4**	**F5**
Sumatriptan	96.16	96.16	96.16	96.16	96.16
HPMC K4M	150	75	150	75	60
Sodium alginate	100	75	200	75	60
Extracted Biopolymer	-	300	-	350	300
Glycerine	-	1	-	-	-
PEG-400	1	-	1	1	0.75
Water	10	10	10	10	10

The desired drug content in the small patch = 5 mg/cm^2 Area of the small square patch = 2x2= 4cm^2

The total amount of drug to be loaded = Area of petri dish x Desired drug content in the small patch/area of a small square patch

= 38.465 x 10/4 = 96.16 mg

CHARACTERIZATION OF PREPARED SUMATRIPTAN TRANSDERMAL FILMS

Physical appearance:

All of the prepared patches were assessed for colour, clarity, flexibility, and smoothness.

Thickness uniformity:

The thickness of a circular film was measured at three separate sites with a micrometre screw gauge, and the average thickness was calculated. The same was done for the other films as well. **[18]**

Weight variation:

Transdermal film weight variation was evaluated by individually weighing 10 randomly selected films of size 4cm^2 on a digital weighing scale and computing the average weight. Individual film weights should not deviate much from the average weight.

Tensile strength:

The strength of film was calculated using a Tensilometer. It has two load cell grips. The bottom one was fixed, while the top one was adjustable. Film strips were placed b/w these cell grips and progressively applied tension until the film broke. The dial reading in kilogrammes was used to compute the tensile strength**.**

Moisture absorption studies:

After 24hours of placing the films at room temperature in a desiccator containing silica gel, the film was considered and then transferred to another desiccator with a standard KCL solution of 85 percent relative humidity (RH) at room temperature and enabled balance. The transdermal films were repeatedly weighed until they revealed a consistent weight. The capacity to absorb moisture was calculated using the formula given.

Percentage moisture uptake = [Final wt. −Initial wt./Initial wt.] ×100

Moisture loss:

To assess the moisture content of transdermal films, they were weighed separately and stored at room temperature in a desiccator containing calcium chloride for 24 hours. The
final weight of each formulation films was noted when these are does not change in their weight further. The films were weighed repeatedly until their weight remained consistent. **Percentage moisture loss = [Initial wt. −Final wt./Final wt.] ×100**

Drug Content:

The transdermal film was cut into area of 2x2cm^2 and put in a volumetric container. Phosphate buffer pH 7.2 was applied and shaken for 12hrs on orbital shaker and allow for sonication for 10min, then centrifuge at 4000rpm for 15min, filtered this by Whatman filter paper. Finally, the obtained filtrate to taken out 1ml of sample in a test tube and dilution is performed when needed with same solvent. Absorbance of mixture has been determined through means of UV spectrophotometer at 227 nm. The respective placebo film was taken as blank solution. Drug content was evaluated by following formula.

Drug content = (concentration x dilution factor x volume taken)

In-vitro Drug Release Study:

In-vitro drug release study was carried out using a Modified diffusion cell with a capacity of 300 ml. For the determination of the drug release of the prepared transdermal films was identified with the help of cellulose acetate membrane.

This semi-permeable cellulose acetate membrane was being mounted on the glass tube of diameter 2.5cm and dip in 500ml of beaker containing 300ml of pH buffer 7.2. After preparing the transdermal film of Sumatriptan using isolated biopolymer (*Oryza sativa L.*), it was placed on the cellulose acetate membrane. The phosphate buffer pH 7.2 is being used in the receptor compartment of the diffusion cell, Then the complete assembly is placed on a magnetic stirrer with temp. controlling, and magnetic beads are continuously stirring the solution which is present in the receptor compartment, and the temperature was kept at 32
±0.5°C, because temperature of human skin is usually 32°C. The sample were withdrawn at time intervals of 15 min, 30 minutes, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h and analysed for drug content at wavelength of 227 nm using a UV double-beam spectrophotometer. Each time a sample was withdrawn, equal volume of phosphate buffer is replenished in the receptor phase of diffusion cell. An equation derived from a calibration curve was used to calculate cumulative percentage drug release.

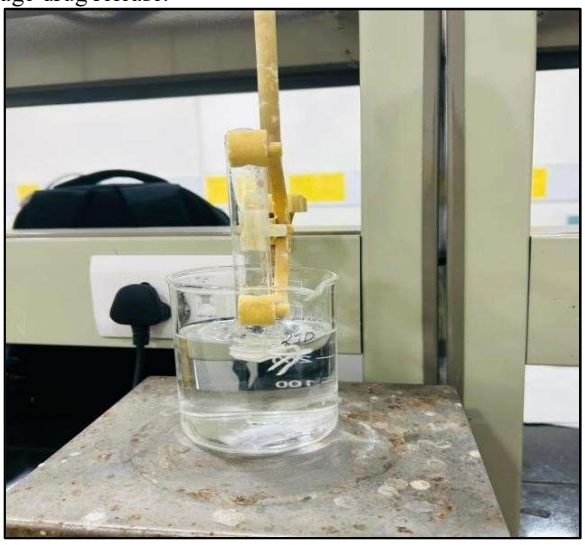


Fig.1: Modified diffusion cell

RESULTS

Organoleptic Properties

The drug had a proportionate physical appearance, colour, and crystalline nature.

Melting Point

The melting point of sumatriptan was found to be 170.64ºC.

UV Spectroscopy

Determination of λmax and Calibration curve of Sumatriptan

Spectrophotometric scanning of Sumatriptan

By scanning 10 µg/ml concentration solution in the range of 200-800nm, λ_{max} of Sumatriptan in pH 7.2 phosphate buffer was found to be 227 nm.

Table 8: Calibration data of Sumatriptan with pH 7.2 phosphate buffer at 227nm

Concentration (µg/ml)	Absorbance
2	0.141
4	0.261
6	0.372
8	0.481
10	0.603
12	0.732
14	0.829
16	0.944

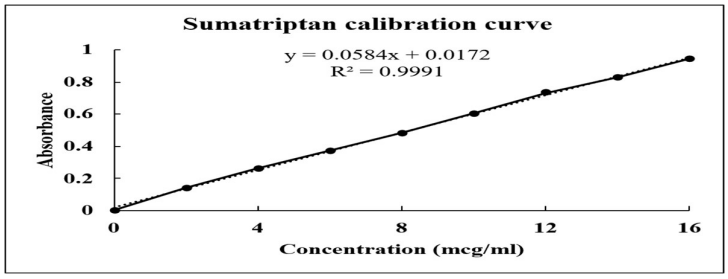


Fig. 2: Calibration curve of Sumatriptan at 227 nm

Page: 1817

4.5 Fourier Transform Infra-red (FTIR) Spectroscopy

The FT-IR spectra of drug Sumatriptan and its physical mixtures with the excipients were recorded in the range 400-4000 cm-1.

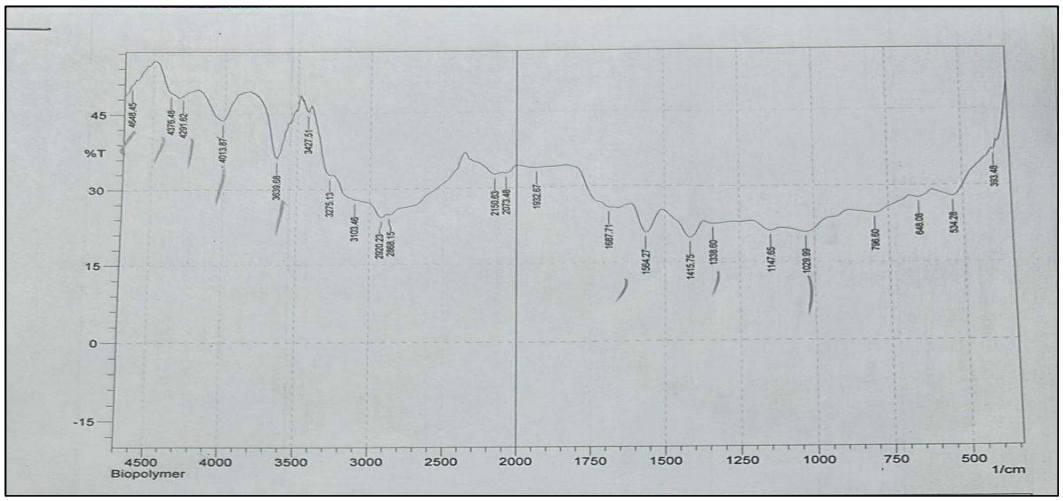


Fig. 3: FT-IR of extracted Biopolymer (*Oryza sativa L*)

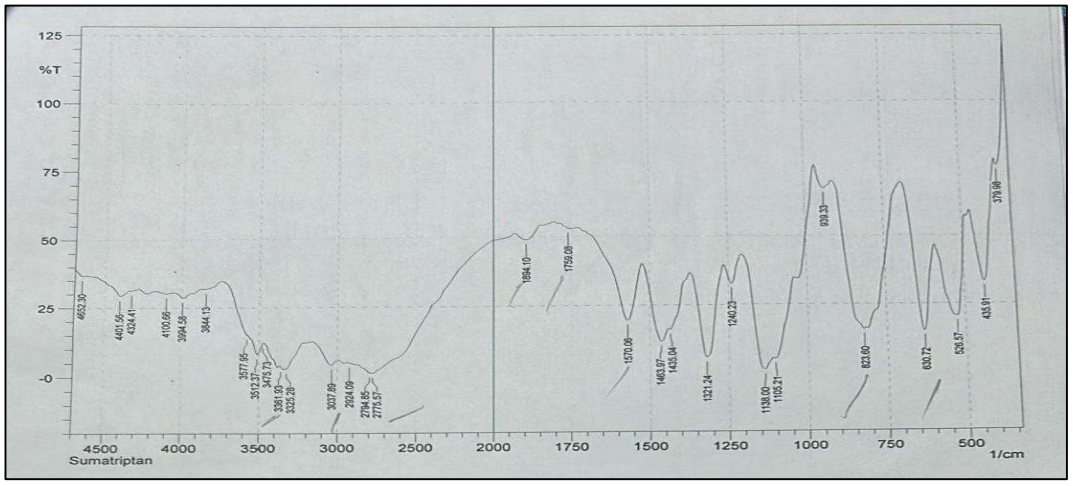


Fig. 4: FT-IR of drug Sumatriptan

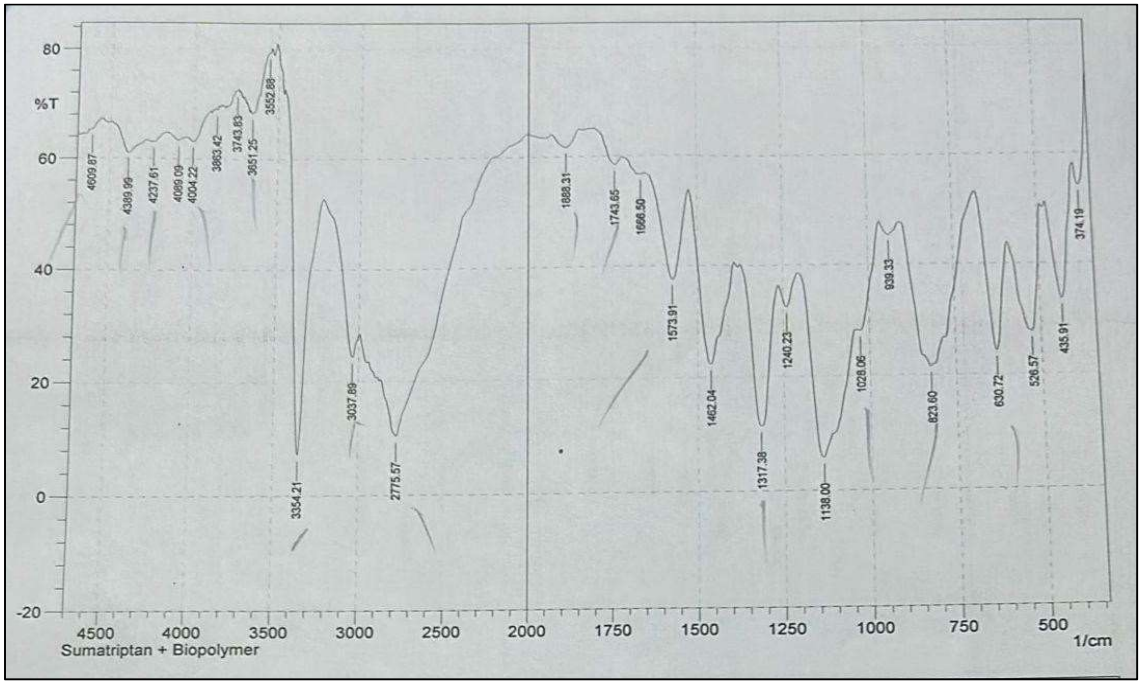


Fig. 5: FT-IR of drug Sumatriptan + Isolated Biopolymer

Differential Scanning Calorimetry (DSC)

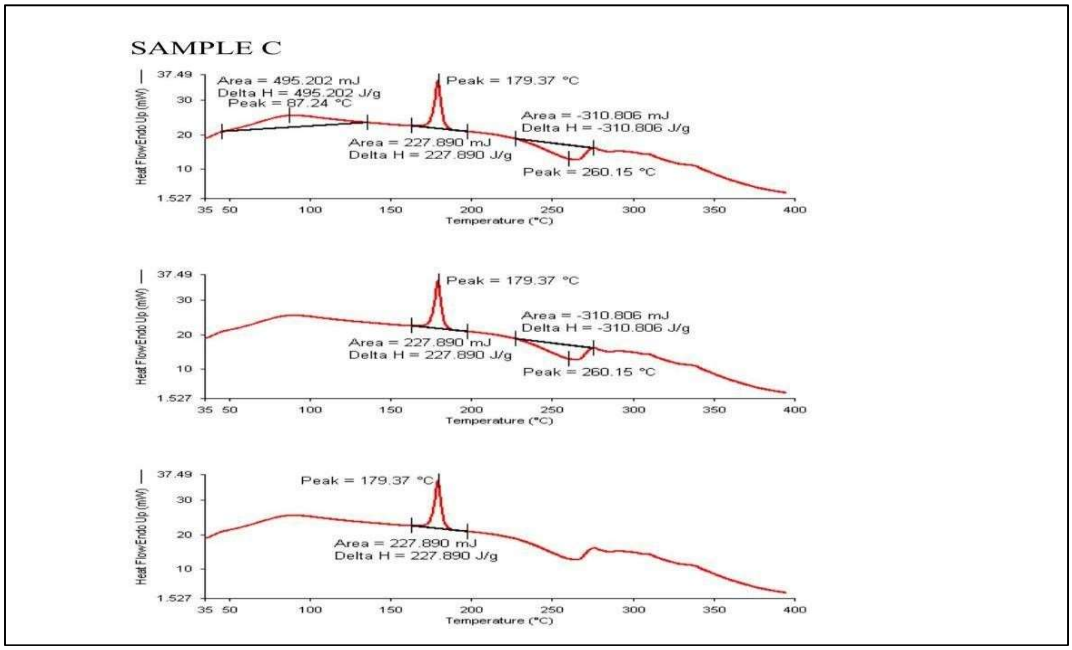


Fig. 6: DSC of Drug Sumatriptan+ isolated biopolymer

CHARACTERIZATION OF PREPARED SUMATRIPTAN TRANSDERMAL FILMS

The physicochemical properties of fabricated transdermal films were tested, including physical appearance, thickness, weight uniformity, drug contents, moisture contents, moisture absorption, flatness, folding endurance, tensile strength, and ph.

Physical appearance

All the films were visually assessed for their uniformity, surface texture, flexibility, clarity, and smoothness, and free from the entrapment of air bubbles as illustrated in Fig. 7.

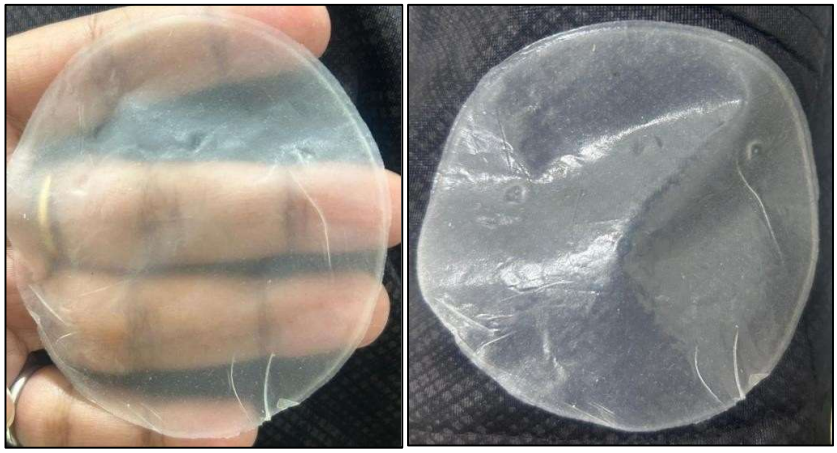


Fig. 7: Fabricated Sumatriptan transdermal biofilms.

Table 9: Characterization of Transdermal films

Formulation code	Thickness (mm)	FE	Weight (mg)	PMC (%)	PMA (%)	Tensile strength	Drug content	pH
F1	0.25	98	121.32	1.03	2.22	0.33	99.15	6.24
F2	0.23	104	122.65	1.44	2.53	0.45	98.43	6.5
F3	0.24	110	123.82	1.23	3.29	0.67	99.65	6.8
F4	0.26	108	120.87	1.96	2.77	0.35	99.87	6.43
F5	0.21	102	123.50	1.87	2.65	0.28	98.34	5.92

IN-VITRO DRUG RELEASE STUDY

Transdermal film diffusion studies are critical to ensuring a control release pattern. To maintain a constant permeation of drug release rate, one must maintain the concentration of drug on the stratum corneum surface dependably and afterward more than plasma's drug concentration. The modified diffusion cell using phosphate buffer solution pH 7.2 as a dissolution medium at 32 ± 0.40 °C was used to conduct the diffusion study. The results of in-vitro diffusion studies of fabricated transdermal films are shown in the Fig. 8

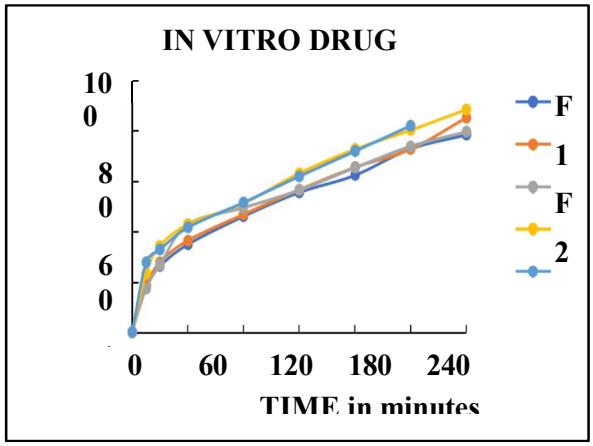


Fig. 8: Release profile of Sumatriptan transdermal films (F1-F5)

In F4 88.34% drug was released which is considered as the optimized formulation but as we can see in the above charts other formulations didn't perform well.

IN-VITRO RELEASE KINETICS

For formulation F4

The values of *in-vitro* diffusion of Formulation F4 were put into the kinetic models and the results are shown in the following figures

Log % CDR

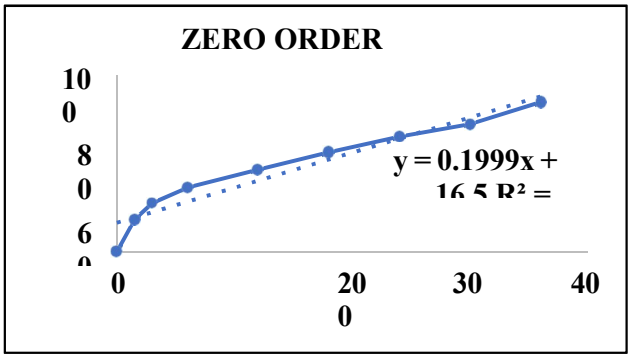


Fig. 9: Zero order kinetics for

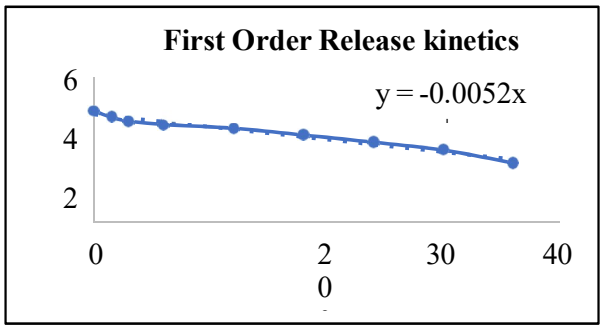
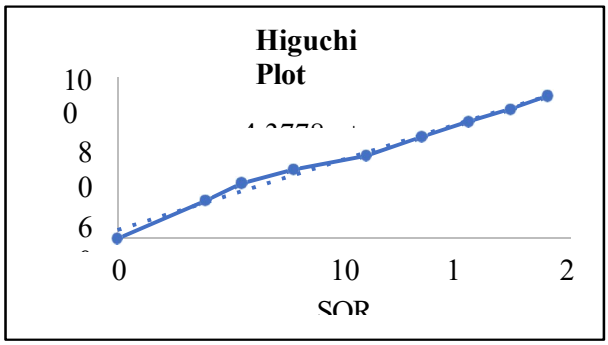


Fig. 10: First order kinetics for



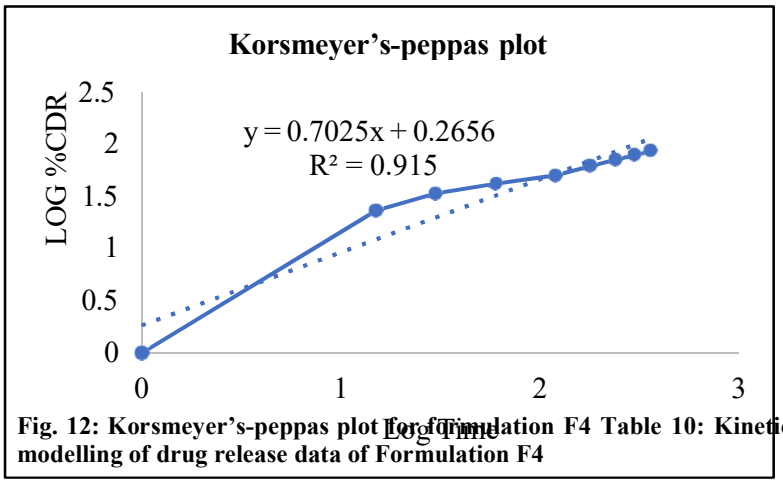


Fig. 12: Korsmeyer's-peppas plot for formulation F4 Table 10: Kinetic modelling of drug release data of Formulation F4

Formulation	Zero order	First order	Higuchi Release kinetics	Korsmeyer's peppas Release Kinetics
	R^2	R^2	R^2	R^2
F4	0.9255	0.9761	0.9888	0.915

The optimized Formulation F4 follows mixed order kinetics with an R^2 value of 0.9255 and 0.9761 of zero order and first order respectively. Best fit model is Higuchi model shows highest (R^2=0.9888) indicating its release pattern.

RESEARCH OUTCOMES

The present study successfully developed and evaluated sumatriptan succinate-loaded transdermal films using biopolymer extracted from poha (flattened rice, *Oryza sativa* L.) via solvent casting technique as a novel gastric-independent delivery system for acute migraine therapy.

Sumatriptan succinate, along with permeation enhancers, plasticizer (PEG 400), and co-processing agents, was incorporated into *Oryza sativa* L. starch matrix, achieving controlled release suitable for bypassing first-pass metabolism and gastric stasis limitations.

FTIR and DSC analyses confirmed no physicochemical interactions between drug, biopolymer, and excipients, ensuring molecular stability.

Physicomechanical evaluation indicated optimized formulation F4 exhibited excellent tensile strength (0.35 kg/cm²), folding endurance (>300), and uniform drug content (98.87%).

In vitro release studies demonstrated F4 released 88.34 % drug over 6 hours following mixed order kinetics (zero-order kinetics R^2=0.992 and first order kinetics R^2 =0.9761), ideal for sustained migraine relief.

Thus, *Oryza sativa* L. starch-based transdermal films provide a biocompatible, cost-effective alternative to conventional sumatriptan formulations, addressing key pharmacokinetic limitations during migraine attacks.

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