Response surface methodology and optimized synthesis of guar gum-based hydrogels with enhanced swelling capacity†

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Guar gum based hydrogel was optimally synthesized using a response surface methodology (RSM) approach for enhanced swelling capacity. Maximization of the water absorption capacity of the synthesized hydrogel was achieved through sequential experimental design based optimization. A fractional factorial screening (Resolution-IV) approach was used to screen significant process variables for maximization of percentage swelling in phase-1. Studied reaction parameters were: (i) monomer concentration, (ii) initiator concentration, (iii) cross linker concentration, (iv) polymerization time, (v) reaction temperature, (vi) vacuum level, and (vii) pH of reaction mixture. A Pareto chart indicated monomer concentration, pH and initiator concentration as significant process variables which were further optimized using full factorial design (23) in phase-2. RSM based center composite design (CCD) was applied to maximize the percentage swelling for the two most significant variables (pH and initiator concentration) in phase-3. Statistical modeling using ANOVA predicted a near neutral range for pH (~7.0) and an initiator concentration of 21–23 × 10−6 mol L−1 as optimum operating conditions for maximizing the percentage of swelling (5307%). Hydrogels were found to be highly pH sensitive and should be kept in a narrow range for maximization of percentage swelling. Thus, the sequential experimental design was helpful in achieving two fold increases in percentage swelling in a systematic way. Synthesized super absorbent polymers can be used as effective water-saving materials for horticultural and agricultural applications.

1. Introduction

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for modeling and process optimization in which a relevant response is influenced by several variables and the objective is to optimize this response. Central composite design (CCD) is used extensively in building the second order response surface models. Moreover, it is easy to estimate the parameters in a second-order model using the method of least squares and this is used in the optimization process studies.1–3 Screening and RSM optimization for synthesis of a Gum tragacanth–acrylic acid based device for in situ controlled cetirizine dihydrochloride release has been studied.4 The optimization of lactic acid production, focusing on medium supplementation, temperature and pH control has been studied using RSM.5 Response surface methodology has been successfully used to model and optimize biochemical and biotechnological processes related to food systems.6,7 The synthesis and optimization of a soy protein fiber based graft copolymer through response surface methodology has been studied for removal of oil spillages.8 Response surface methodology has been used to study the process optimization of cationic percentage through grafting diallyldimethylammonium chloride (DADMAC) into cassava starch.9 The optimization of novel nanocomposites based on poly(carbonate-urea) urethane and polyhedral oligomeric silsesquioxanes (POSS) has been used in medicine especially in cardiovascular applications employing response surface methodology.10 In that study, design of experiment methodology was used to develop a predictive model to optimize the operating conditions for grafting controlled amounts of carboxylic functional groups onto the surface of POSS–PCU, which could then be used for the coupling of ECM proteins. RSM was used to investigate the effect of five selected factors on the selective H2SO4 hydrolysis of waxy maize starch granules.11 In addition, RSM based Box–Behnken design (BBD) was used to optimize the preparation parameters of a hydrogel consisting of polyvinyl alcohol (PVA), acrylic acid (AA) and taurmaline (Tm).12

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Interpenetrating polymer network (IPN) hydrogels have generated considerable interest among the scientific community because of their diversified applications. Hydrogels form the largest class of biocompatible materials because they resemble natural tissue more than any other class of biomaterials due to their high water content, soft and rubbery consistency and low interfacial tension with water or biological fluids. These are polymeric materials that do not dissolve in water at physiological temperature and pH but swell considerably in an aqueous medium and demonstrate extraordinary capacity (>20%) for imbibing water into the network structure. Hydrogels can also be categorized into conventional and stimuli responsive hydrogels. These polymers are coined with different names, based on their physical or chemical properties. Smart hydrogels are very different from inert hydrogels in that they can ‘sense’ changes in environmental properties and respond by increasing or decreasing their degree of swelling. Hydrogels can be prepared by simultaneous copolymerization and cross-linking of one or more functional monomers. Most optimization studies during the development of a novel hydrogel involve variation of one factor at a time, keeping all other factors constant. This traditional optimization method is time-consuming and expensive. Today, a statistical-based technique of response surface methodology (RSM) is used extensively to elucidate the interaction between reaction parameters for optimization. RSM is a technique whereby reaction parameters are varied simultaneously in a suitable manner to generate data for development of empirical models. It is a faster and more economical analytical approach than the traditional one.

The current study aims to screen important process variables and conduct process optimization using the response surface methodology (RSM) approach for the development of guar gum based hydrogels with improved swelling. There is scant information in the literature on graft copolymerization of acrylic acid onto guar gum, and novelty in the present study lies in the use of the RSM approach for optimization. Moreover, reactions were carried out in green solvent i.e. water and further reaction steps were reduced using an intelligent experimental design strategy.

2. Experimental section

2.1 Materials and methods

Guar gum (Ggum) and ammonium persulfate (APS) were used as backbone and initiator and both were purchased from SdFine Chemicals Pvt. Ltd. The crosslinker agent, hexamine (Loba-Chemie Ltd.) and monomers, acrylic acid (AA) and aniline (Loba-Chemie Ltd.) were used as received. Hydrochloric acid was purchased from Merck India. Solutions with different pH values were prepared by using HCl (0.1 N) and NaOH (0.1 N) solutions. The pH value of the solutions was determined by a pH meter (Cyberscan 1100, EUTECH INSTRUMENTS). Distilled water was used for all reactions. The reactions were carried out under vacuum (600 mm of Hg).

2.2 Synthesis of guar gum-polyacrylic acid based hydrogels

Ggum was graft copolymerized with acrylic acid using ammonium persulfate as an initiator and hexamine as a cross-linker through a free radical polymerization technique in order to obtain a polymer matrix. Ggum (1 g) was dissolved in a known amount of distilled water (20 ml) in a 100 ml beaker. A calculated amount of ammonium persulfate (0.219 × 10⁻³ mol L⁻¹) as an initiator and acrylic acid (0.145 × 10⁻³ mol L⁻¹) as monomer were added drop wise followed by addition of hexamine with continuous stirring. The reaction mixture was continuously stirred to attain homogeneity. The beaker was kept under vacuum for a fixed time period to get the final product. The resulting product was washed with distilled water in order to separate homopolymer. Finally, the product, guar gum-polyacrylic acid (Ggum-cl-poly(AA)), was dried in the hot air oven at 50 °C. Various reaction parameters such as monomer concentration, initiator concentration, crosslinker concentration, polymerization time, vacuum level, reaction temperature and pH of the reaction mixture were optimized to get the maximum percentage swelling (Pₛ).

2.3 Synthesis of guar gum-polyacrylic acid–polyaniline based hydrogels

Ggum-cl-poly(AA-ipn-PANI) was synthesized by adding a calculated amount of Ggum-cl-poly(AA) (1 g) in 30 ml of distilled water. Ggum-cl-poly(AA) was further crosslinked with polyaniline (PANI) under acidic (0.438 × 10⁻³ mol L⁻¹) and neutral conditions (0.548 × 10⁻³ mol L⁻¹) to obtain interpenetrating networks (IPNs). The reaction mixture was kept at room temperature for 16 h, which resulted in the absorption of aniline monomer in the Ggum-cl-poly(AA) network and the formation of a swollen sample. After 16 h, pre-optimized ammonium persulfate and hexamine were added with continuous stirring. When a pre-optimized amount of thermal initiator was added slowly into the reaction mixture at the polymerization step, the slightly brown color of the reaction solution changed to slightly green. Thereafter, the reaction was again carried out under vacuum for a fixed time under pre-optimized reaction conditions. The resulting product was washed with 1-methyl-2-pyrrolidone to remove homopolymer. Finally, the product was dried in a hot air oven at 50 °C overnight and thus a solid Ggum-cl-poly(AA-ipn-PANI) IPN structure was obtained. Optimization was done with respect to aniline concentration.

2.4 Experimental design and model development for Ggum-cl-poly(AA)

Percentage swelling (Pₛ) of the synthesized hydrogel is dependent on many process factors like initiator concentration, reaction time, pH, monomer concentration, reaction temperature, crosslinker and vacuum applied. Testing all these variables using a one factor at a time approach (OFAT) is time consuming and also eliminates the two factor interactions (2FI) between independent variables. Frequently, 2FI exist in hydrogel synthesis since there may be antagonistic or synergistic
effects between independent variables. This indicates the need to run a full factorial design, where all the probable combinations are tested. However, the biggest disadvantage to this is the enormous amount of experimental work required for a high number of variables [e.g. 7 variables varied at maximum and minimum level would result in $2^7$ (128) experimental runs]. Thus, to reduce the experimental work, intelligent experimental design using fractional factorial design (Resolution-IV) was employed to screen the significant process variables. Seven variables were varied at maximum (+1) and minimum (−1) levels for maximizing percentage swelling of the graft copolymer. Resolution-IV design includes all main effects along with some 2FI. Although there is 2FI aliasing, this is taken care of using process understanding. Pareto charts along with half normality plots were used for selection of significant process variables for maximizing percentage swelling. The experimental data was fitted using sequential ANOVA modeling and model significance was tested based on probability values ($p$-values) with non-significant lack of fit (an indication of higher signal than noise). The numerical optimization of the selected model was performed to maximize swelling rate with minimum standard error of predictions using a desirability function. Finally, the two most significant process variables (pH and initiator concentration) were optimized using center composite design (CCD). CCD has 5 levels for each factor and is used for second order model building using response surface methodology (RSM).

2.5 Swelling behaviour of hydrogel

Various reaction parameters were optimized with respect to percentage swelling ($P_s$) using a fractional factorial design approach during screening experimentation and results were used for developing response surface models. The swelling ratio was defined as the ratio (wet weight – dry weight)/(dry weight). Swelling behavior of the hydrogels was investigated in distilled water. After definite time intervals, samples were wiped and weighed. The process was repeated until equilibrium was achieved i.e. 16 h. After weighing the swollen hydrogel on an analytical balance (accuracy ± 0.00001 g), percentage swelling ($P_s$) was calculated by using the following equation: \[ P_s = \frac{W_s - W_d}{W_d} \times 100 \] (1)

where, $P_s$ = percentage swelling (%) and $W_s$ and $W_d$ are the weight of swollen and dry hydrogel respectively.

2.6 Characterization of synthesized hydrogels

FTIR spectra of Ggum and the synthesized hydrogels were taken on a Perkin Elmer spectrophotometer using the KBr pellet method. FTIR spectra of the samples were taken in the range of 400–4000 cm$^{-1}$ with a resolution of 2 cm$^{-1}$. Thermal properties of synthesized samples were studied with a TG/DTA 6300, SII EXSTAR 6000 in a nitrogen atmosphere at a heating rate of 10 °C min$^{-1}$. The morphology of the candidate polymers was studied using the scanning electron microscope LEO-435VF.

3. Results and discussion

3.1 Synthesis of hydrogel networks

Phase-1: screening of significant variables. A total of 19 experimental runs were performed to screen significant process variables as per Resolution-IV design (Table S1†). The seven variables were studied simultaneously at maximum and minimum levels viz. initiator concentration (17.5 × 10$^{-3}$–35 × 10$^{-3}$ mol L$^{-1}$), reaction time (60–90 min), pH (6.5–7.5), monomer concentration (145 × 10$^{-3}$–290 × 10$^{-6}$ mol L$^{-1}$), reaction temperature (40–80 °C), crosslinker (42.7 × 10$^{-3}$–64.1 × 10$^{-3}$ mol L$^{-1}$) and vacuum (400–800 mm of Hg) and the percentage swelling ($P_s$) was measured as the response. The maximum and minimum percentage swellings were 4724% and 2721% respectively. A half probability plot along with a Pareto chart predicted that monomer, pH and initiator concentration have significant effects on response data (graphs not given). Also, significant 2FI was observed between initiator concentration × pH and initiator concentration × monomer. Thus, five model terms (3 main effects plus two 2FI) were selected for model building. The ANOVA model was highly significant and passed the diagnostic testing for a normal plot of residual test (Fig. S1†). The process indicated that lower values of initiator, pH and monomer are recommended for maximizing percentage swelling. Also, there is an antagonistic interaction between initiator concentration × pH, whereas a synergistic 2FI between initiator concentration × monomer is observed. The optimized process conditions for maximizing of percentage swelling (4030%) are an initiator concentration of 24.6 × 10$^{-3}$ mol L$^{-1}$, a pH of 6.86 and a monomer concentration of 188.3 × 10$^{-6}$ mol L$^{-1}$.

Phase-2: full factorial design. In phase-2, initiator concentration, pH and monomer were taken as important process factors. The fixed process conditions were 75 min reaction time, 60 °C reaction temperature, 53.4 × 10$^{-3}$ mol L$^{-1}$ of crosslinker and vacuum of 600 mm of Hg. Full factorial design (2$^3$) with 3 center runs was performed (Table S2†). The three significant variables were studied in the modified range viz. initiator concentration (17.5 × 10$^{-3}$–35 × 10$^{-3}$ mol L$^{-1}$), pH (6.25–7.0), and monomer concentration (116 × 10$^{-6}$–217.5 × 10$^{-6}$ mol L$^{-1}$). A Pareto chart gave pH and initiator concentration as the most significant process parameters, indeed pH was highly significant with variables exceeding Bonferroni limits (Fig. S2†). The fitted ANOVA model has excellent prediction capability (Table S2†). The monomer concentration was not a part of model building and was kept constant at 166.8 × 10$^{-6}$ mol L$^{-1}$. The numerical optimization was achieved at pH 6.78 and an initiator concentration of 21.6 × 10$^{-6}$ mol L$^{-1}$ for maximizing percentage swelling at 4819%.

Phase-3: center composite design. The most popular RSM design is the central composite design (CCD) having three groups of design points, viz. factorial design points, axial or star points and center points (Fig. S3†). CCD is generally designed to estimate the second order regression modelling. Two factor center composite design (CCD) was used for optimization of pH and initiator concentration for maximizing percentage of swelling. The effect of pH was studied in the range of 6.65–7.35
and initiator concentration was studied between $17.5 \times 10^{-6}$ and $30.6 \times 10^{-6}$ mol L$^{-1}$. Monomer concentration was fixed at $166.8 \times 10^{-3}$ mol L$^{-1}$. Each variable was varied at 5 levels (−α, −1, 0, +1, +α) having 13 experimental runs (Table S3†). The ANOVA model fitted well to the response data. The model statistics are given in Table S3†. The model passed the diagnostic tests for any outliers including normal probability plot.

The 3D response plot between initiator concentration vs. pH vs. percentage swelling is depicted in Fig. 1. The optimized process conditions for maximum swelling (5307%) were a pH of 6.95 and an initiator concentration of $22.3 \times 10^{-3}$ mol L$^{-1}$. The percentage swelling is more sensitive to pH, with acidic conditions decreasing percentage swelling at a faster rate than basic conditions. Although the authors believe that a monomer concentration of $217.5 \times 10^{-6}$ mol L$^{-1}$ instead of $166.8 \times 10^{-6}$ mol L$^{-1}$ will further enhance the swelling capacity, this aspect needs verification. The proposed conditions were revalidated.

3.2 Characterization of synthesized hydrogels

**FTIR**. The crosslinking was determined on the basis of IR spectra of guar gum, Ggum-cl-poly(AA) and Ggum-cl-poly(AA-ipn-PANI). The FTIR spectra of Ggum, semi-IPN and IPNs are shown in Fig. 2. In the case of Ggum (Fig. 2a), the broad peak at 3444.10 cm$^{-1}$ indicates the presence of OH stretching vibrations of the gum polysaccharide and peaks observed at 2921.17 and 1025 cm$^{-1}$ show C–H stretching modes and O–H bending vibrations, respectively. The peak at 1650 cm$^{-1}$ was assigned to the stretching vibration of the –C==O in a carbonyl group. In the case of Ggum-cl-poly(AA), the appearance of a new band at 1732.69 cm$^{-1}$ which is due to carbonyl stretching of carboxylic acid along with other bands confirms the formation of a graft copolymer (Fig. 2b). The bands at 1732.69 cm$^{-1}$ correspond to an out-of-plane C–H bending vibration of carboxyl groups. Interestingly, the peaks after grafting shifted to a higher wave number region indicating the formation of cross-linked hydrogel. The bands at 732 cm$^{-1}$ correspond to an out-of-plane C–H bending vibration of para-disubstituted rings. Similarly in the case of Ggum-cl-poly(AA-ipn-PANI), additional peaks at 1405.59 and 1406.35 are due to C–N stretching modes, confirming the formation of IPNs (Fig. 2c and d). It has been reported that the band at 1027 cm$^{-1}$ provides a measure of the degree of the delocalization of electrons and also reveals high conductivity. The shifting and the formation of new bands

![Fig. 1 3D plot of pH and initiator concentration vs. percentage swelling rate (Ps) as per phase-3.](image1)

![Fig. 2 FTIR spectrum of (a) Ggum; (b) Ggum-cl-poly(AA); (c) Ggum-cl-poly(AA-ipn-PANI) – neutral conditions, and (d) Ggum-cl-poly(AA-ipn-PANI) – acidic conditions.](image2)
provide support for the formation of Ggum-cl-poly(AA-ipn-PANI) hydrogel. Thus, it is quite evident from FTIR studies that chains of acrylic acid and aniline were grafted onto guar gum.

Surface morphology. The surface morphology of the guar gum and its amalgamated structures are shown in three states: native, crosslinked and layered/hybrid with polyaniline. The surface morphology of Ggum, Ggum-cl-poly(AA) and Ggum-cl-poly(AA-ipn-PANI) were studied by scanning electron microscopy. SEM of Ggum, Ggum-cl-poly(AA) and Ggum-cl-poly(AA-ipn-PANI) clearly shows the morphological changes in the features of Ggum after grafting and networking with polyacrylic acid and polyaniline. Moreover, crosslinking of different polymeric chains with hexamine further added to the morphological transformations. Pure Ggum (Fig. 3a) has a smooth surface with small dots on the surface. Ggum-cl-poly(AA) (Fig. 3b) and Ggum-cl-poly(AA-ipn-PANI) (Fig. 3c and 3d) have coarse surfaces due to graft copolymerization and cross-linking. After the cross linking of guar gum with poly(AA), the structural morphology is changed and resembles a whisker like morphology with a rough agglomerated surface. These figures display the favorable cross linking network between guar gum and poly(AA). These micrographs clearly show the variation in chemical structures and changed surface morphology in cross linked networks.23,24

Thermal properties. Thermogravimetric analysis of Ggum, Ggum-cl-poly(AA), Ggum-cl-poly(AA-ipn-PANI) – neutral conditions and Ggum-cl-poly(AA-ipn-PANI) – acidic conditions are depicted in Fig. 4. It has been observed that grafting of polyacrylic acid, polyaniline and crosslinking have changed the thermal behavior of Ggum. Synthesized hydrogels were found to be thermally more stable than Ggum. In pure Ggum, a two stage decomposition was observed. In the beginning, only 9.1% weight loss was observed up to 247 °C. The maximum weight loss (54.9%) was observed from 247 to 330 °C due to the degradation of the backbone polymer. Additionally, 13.55% and 4.23% weight loss were observed in the temperature ranges 330–500 °C and 500–700 °C, respectively. In the case of Ggum-cl-poly(AA), Ggum-cl-poly(AA-ipn-PANI)-neutral conditions and Ggum-cl-poly(AA-ipn-PANI) – acidic conditions, a three stage decomposition was observed. In the case of Ggum-cl-poly(AA), only 5.51% weight loss was observed up to 200 °C. Maximum weight loss i.e. 35.81 and 17.94 was observed in the temperature ranges of 200–365 °C and 365–450 °C, respectively. After 450 °C, 10.98% weight loss was observed up to 700 °C. Maximum weight loss up to 365 °C was due to the breaking down of crosslinked polymeric chains and further weight loss was due to the degradation of the individual components like polyacrylic acid chains, Ggum and the crosslinker.27

A similar observation was made in the case of IPNs prepared under neutral and acidic conditions. In the case of Ggum-cl-poly(AA-ipn-PANI) prepared under neutral conditions, initially 13.06% weight loss was observed up to 225 °C. Weight losses of 30.28 and 20.55% were observed in the second degradation stage (225–300 °C) and third degradation stage (300–450 °C), respectively. A further 9.81% weight loss was observed from 450 to 700 °C. In the case of Ggum-cl-poly(AA-ipn-PANI) prepared under acidic conditions, 14.85% weight loss was observed.

Fig. 3  SEM of (a) Ggum; (b) Ggum-cl-poly(AA); (c) Ggum-cl-poly(AA-ipn-PANI) – neutral conditions, and (d) Ggum-cl-poly(AA-ipn-PANI) – acidic conditions.

Fig. 4  TGA of (a) Ggum; (b) Ggum-cl-poly(AA); (c) Ggum-cl-poly(AA-ipn-PANI) – neutral conditions, and (d) Ggum-cl-poly(AA-ipn-PANI) – acidic conditions.
initially up to 200 °C. The second degradation stage (200–400 °C) and third degradation stage (400–500 °C) showed 39.11 and 19.13% weight loss, respectively. A further 5.94% weight loss was observed from 500 to 700 °C. A slight increase in the degradation temperature of the third stage was observed due to the crosslinked networking structure.

4. Conclusions

Sequential experimental design strategy was successful in improving the swelling capacity of a Guar gum based hydrogel by two fold to 5307%. Resolution-IV design was used for screening of important variables followed by two level three factor (2³) full factorial design. Finally, the two most significant process variables (pH and initiator concentration) were optimized using response surface plots and numerical optimization. Hydrogel is highly pH sensitive and best results were obtained near neutral pH (~7.0), with an optimum initiator concentration of 22.3 × 10⁻³ mol L⁻¹ for maximizing swelling rate. The other optimized parameters were monomer concentration of 166.8 × 10⁻⁶ mol L⁻¹, reaction time of 75 min, reaction temperature of 60 °C, crosslinker concentration of 53.4 × 10⁻³ mol L⁻¹ and vacuum of 600 mm of Hg. Finally, validation experiments proved the effectiveness of the model. Superabsorbent polymers can absorb a large amount of water compared with general water absorbing materials and absorbed water is hardly removable even under some pressure. Synthesized superabsorbent polymers can be used as an effective water-saving material for horticultural and agricultural applications.

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