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Optimisation of enzymatic liquefaction and spray drying of Papaya (*Carica papaya*) processing waste for production of nutrient rich powder

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Abstract
Papaya processing generates substantial quantities of waste rich in bioactive compounds, yet its utilization remains limited. The present study aimed to valorise papaya processing waste through enzymatic liquefaction followed by spray drying to produce a stable nutrient-rich spray-dried powder. Enzymatic liquefaction of papaya waste using pectinase was optimized employing response surface methodology (RSM) with a central composite rotatable design, considering enzyme concentration (0-2%), reaction time (30-120 min), and temperature (25-100 °C) as independent variables. Juice yield, clarity, and total soluble solids (TSS) were selected as response parameters. The optimized conditions were determined to be 1.25% pectinase concentration, 79.33 min reaction time, and ~50 °C temperature, yielding 82.79±2.27% juice yield, 39.00±2.28% clarity (%T), and 14.70±0.16 °Brix TSS, closely matching predicted values and confirming model adequacy. The optimized liquefied juice was successfully spray dried using 20% maltodextrin at an inlet/outlet temperature of 120/83 °C, resulting in a free-flowing powder with low moisture content (5.49 g/100 g). The spray-dried powder exhibited high carbohydrate content, acceptable retention of carotenoids, improved colour attributes, and spherical particle morphology. Overall, the study demonstrates an integrated and sustainable approach for converting papaya processing waste into a value-added functional powder suitable for food applications, contributing to waste reduction and circular bioeconomy initiatives.

Keywords: Papaya waste, enzymatic liquefaction, pectinase, response surface methodology, spray drying, papaya by-products

1. Introduction
Papaya (*Carica papaya* L.) is widely recognized for its significant nutritional and therapeutic value. Papaya has gained recognition as a nutraceutical fruit owing to the presence of diverse bioactive compounds that contribute to its functional properties. These health-promoting effects are largely attributed to its rich phytochemical composition, which includes proteolytic enzymes such as papain, carotenoids, lycopene, flavonoids, alkaloids, essential minerals, and vitamins. Collectively, these constituents are associated with antioxidant, antimicrobial, wound-healing, and metabolic regulatory activities, reinforcing the importance of papaya as a functional food and a valuable raw material for food and health-related applications (Gunde & Amnerkar, 2016) [8].

Despite its economic importance, papaya processing is associated with substantial post-harvest losses, with approximately 30-50% of the fruit discarded as waste due to grading, peeling, deseeding, trimming, and quality defects (Heller *et al.*, 2015; Sagar *et al.*, 2018) [10, 21, 22]. Processing of papaya produces about 30-35% waste, comprising the out-graded/over-ripe papaya, its skin, seeds, and dices are the common waste produced by the processing industry. Dicing of papaya produces about 8.5% peel waste, 6.5% seeds, 32% unusable pulp (because of imperfections in cubes), and about 53% final product (Sagar *et al.* 2018) [21, 22]. Total rind and seed wastes account for 10-20% as reported by Lee *et al.* (2011) [14] and Parni and Verma (2014) [17]. As per the literature review, this waste is mainly used for the production of biomethanation (Rajivgandhi *et al.* 2013) [19], enzymes (Han *et al.* 2018; Chaiwut *et al.* 2010) [9, 3], and organic acids (Vikas and Mridul 2014) [30]. Among the waste, papaya peel has been explored for food applications as flour (Santos *et al.* 2014) [25] and

pectin (Koubala *et al.* 2014) [13]. Papaya is a rich source of antioxidants like Vitamin C, Vitamin A, and Vitamin E. In addition, it is also a good source of papain digestive enzyme and β-carotene (Vij and Prashar 2015) [28]. Considering the nutrient profile of papaya and the amount of waste produced during processing, an attempt has been made to liquefy papaya waste for its utilization in food product development.

Considering the nutrient-rich composition of papaya and the substantial quantity of waste generated during industrial processing, there is significant potential to valorize this by-product for food applications. Papaya waste, comprising pulp residues, peel, seeds, and rejected fruit portions, retains appreciable amounts of soluble sugars, dietary fiber, carotenoids, and endogenous enzymes. However, the presence of complex pectic substances and fibrous cell wall components limits efficient juice recovery and downstream utilization. Enzymatic liquefaction, particularly using pectinase, offers an effective strategy to overcome these limitations by degrading pectin networks, reducing viscosity, and enhancing juice release. Optimization of the liquefaction process is critical, as papaya waste differs from fresh pulp in composition and structural integrity. When multiple processing variables and their interactions influence extraction efficiency and quality attributes, response surface methodology (RSM) serves as a robust statistical tool for systematic optimization with a reduced number of experimental trials.

The juice obtained from optimized enzymatic liquefaction can be further stabilized through dehydration to enable long-term storage and broaden its application potential, like development of food products. Dehydration not only reduces moisture content and microbial activity but also lowers transportation costs and minimizes packaging requirements. According to Jangam *et al.* (2014) [11] and Mishra *et al.* (2014) [16], dehydration is an ideal technology for fruit and vegetable preservation. Apart from reducing the moisture content and inhibiting the growth of microorganisms and enzyme activity, dehydration also increases the shelf life of the product with reduced transport weight and minimise packaging requirements (Sagar and Sureshkumar 2010) [22]. The most applicable methods of drying include freeze, vacuum, osmotic, spray, cabinet or tray, fluidized bed, spouted bed, ohmic, microwave, and combinations thereof (George *et al.* 2004) [5]. Among all these techniques used for dehydration, spray drying is one of the most extensively used methods for the production of heat-sensitive fruits and vegetables (Kha *et al.* 2010; Wong and Chong, 2015) [12, 4]. By using heat, spray drying rapidly removes liquid from a dilute fluid suspension into a dry powder and renders a good-quality final powder with minimal negative impact on the product. Spray drying involves atomisation, contact between droplets and hot gas, water evaporation, and gas-powder separation (Verma and Singh 2015) [27] to obtain free-flowing powders. Spray drying of fresh papaya pulp has been reported by Gomes *et al.* (2018) [7]. Wong and Lim (2016) [32] studied the storage stability of spray-dried powder packed in different packaging materials. However, an attempt has been made in the present work to utilise industry waste of papaya to spray dry for its application in food product development. While spray drying of fresh papaya pulp and juice has been previously reported, limited information is available on the utilization of papaya processing waste as a spray-dried ingredient. Therefore, integrating enzymatic liquefaction with spray drying presents a promising approach to transform papaya processing waste into a stable, functional powder for food product development.

The objectives of the present study were threefold: (1) to evaluate the effects of enzyme concentration, reaction time, and temperature on juice yield, clarity, and total soluble solids during the enzymatic liquefaction of papaya waste; (2) to optimise these process variables using response surface methodology to establish ideal conditions for maximum extraction efficiency; and (3) to spray dry the optimised liquefied juice to obtain a stable powder suitable for potential food product development. This integrated approach aims to convert underutilised industrial papaya waste into a value-added, nutrient-rich ingredient, thereby supporting sustainable waste management and expanding opportunities for functional food applications.

2. Materials and Methods

2.1 Collection and preparation of Papaya for Spray Drying

The material used for spray drying in the present study was an outcome of the canning process and included out-graded/rejected/overripe/unused papaya, seeds, dices, and peel of the papaya fruit, procured from Tarihal Industrial Area, Hubli, India. The fruit material was transported in an insulated hard plastic container to avoid light and temperature exposure during transportation. The collected papayas were cleaned, pulped, and pasteurised (91 °C for 10 min) (Fig. 1), then ground in a hydraulic press and stored under frozen conditions. The material was brought to room temperature before use.

2.2 Experimental Procedure

2.2.1 Enzymatic treatment

The enzyme pectinase (Commercial Name: Pectinex Ultra SPL; activity 3800 units/mL) from *Aspergillus aculeatus* was procured from Sigma-Aldrich, Bangalore, India. The homogenised pulp (100 g) was treated with pectinase enzyme and incubated in a stirred, temperature-controlled water bath (SCIENTEK Instruments, Bangalore, India) for continuous mixing of the enzyme-treated pulp at the specified temperature and time, as per experimental design (Table 1). Then the suspension was kept at 90 °C for 10 min in a water bath for enzyme inactivation (Sandri *et al.* 2011) [24]. A muslin cloth was used to filter the juice. The filtrate was measured, and the pomace was weighed. The filtrate was taken for further analysis of dependent variables. One sample was kept without enzymatic treatment as a control sample.

2.2.2 Yield

The percentage yield of experimental pulp was centrifuged at 10,000 rpm for 20 min. The juice yield was estimated as per method suggested by Ghosh (2017) [6].

2.2.3 Clarity

The clarity of enzyme-extracted juice was estimated as percentage transmittance (%T) at 660 nm using a UV spectrophotometer (METASH Model UV-5800).

2.2.4 Total Soluble Solids

An Abbe-type refractometer (°Brix) was used to measure the total soluble sugars (TSS) in the sample.

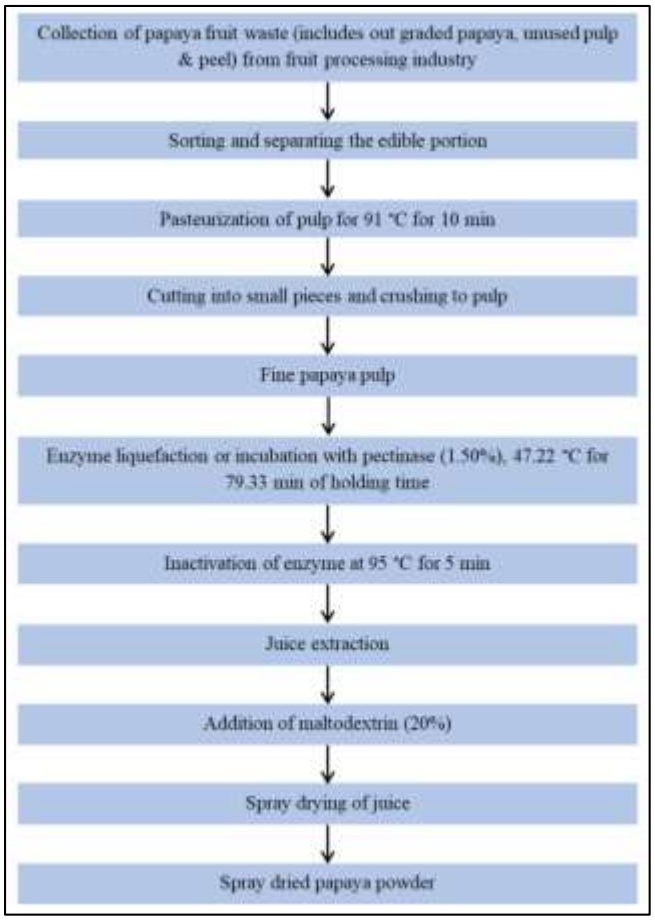


Fig 1: Flow diagram for production of spray dried papaya powder

2.3 Experimental Design

A central composite rotatable design (CCRD) with three variables was used to study the response pattern and determine the optimum combination of variables. The independent variables optimised were enzyme concentration (0-2%), reaction time (30-120 min), and temperature (25-100 °C), each at five levels (Table 1). The dependent variables studied were % juice yield, clarity, and TSS. CCRD was used to optimise the treatment and extraction conditions for papaya juice. Design Expert Software (Version 8.0.7.1) was used for optimisation of independent variables. For enzymatic treatment, the key elements: pectinase concentration, reaction time, and temperature were coded as X_1, X_2, and X_3, respectively.

Table 1: Variables and their levels for central composite rotatable design (CCRD)

Variable	Symbols		Levels				
	Coded	Uncoded	-1.414	-1	0	1	1.414
Pectinase concentration (%)	X_1	x_1	0.00	0.41	1.01	1.60	2.00
Time of reaction (min)	X_2	x_2	0.00	24.32	60.01	95.70	120.00
Temperature (°C)	X_3	x_3	25.00	40.20	62.40	84.80	100.00

X1 = (x_1-1.01)/0.41, X2 = (x_2-60.01)/35.69 and X_3 = (x3-62.40)/22.40

The CCRD setup shown in Table 2 was arranged to allow fitting of an appropriate regression model using a multiple regression programme. The combined impact of these independent variables was studied. A total of 20 experiments with six replications at the centre point were conducted to estimate pure error using the software. Table 2 shows the coded values of the experiments. The experiments were randomised to maximise the effects of unexplained variability due to extraneous factors. To study the effects of variables in terms of linear, quadratic, and interaction terms, a second-order quadratic polynomial equation was used to fit the experimental values in Table 2. The model proposed for the response (Y_1, Y_2, and Y_3) was:

$$Y_i = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3 + \varepsilon$$

Where Y_i (i = 1-3) is the predicted response for yield, clarity, and TSS respectively; a_0 is the intercept, and a_i, a_{ii}, and a_{ij} are the linear, quadratic, and cross-product terms. Optimisation of the fitted polynomials was performed using graphical technique, and the optimum conditions were verified experimentally, and the observed responses were compared with predicted values.

The fitted polynomial equations were expressed as surface and contour plots using statistical software to visualise the relationships between the responses and experimental levels of each factor and to deduce optimum conditions.

2.4 Preparation of Spray-Dried Powder

The enzyme-liquefied juice obtained was used for spray drying. The spray drying conditions were selected as reported by Wong and Lim (2016) [32] with some modifications. The aqueous extract was mixed with 20% (w/w) maltodextrin (DE10-12) as a carrier. The spray-drying conditions were maintained with an inlet/outlet temperature of 120/83 °C, 100% aspirator rate, and 20% pump rate using a Lab spray dryer (Model LSD-48, JISL, Mumbai). After spray drying, the powder produced was collected in a clean container and kept inside desiccators until cooled. After cooling, the powder was weighed, sealed, and stored at 4 °C in the dark for further analysis.

2.5 Characterization of Spray-Dried Papaya Powder

2.5.1 Moisture content

The moisture content of the powder was determined using oven drying. Triplicate samples of papaya fruit powder (25 mg each) were weighed and dried in a vacuum oven at 70 °C for 24 h (AOAC, 2005) [2]. The samples were removed from the oven, cooled in a desiccator, and weighed. The drying and weighing processes were repeated until constant weight was obtained.

2.5.2 Proximate analysis

Ash, fat, carbohydrate, and energy were determined using AOAC methods (975.03, 996.01, and 996.11). Crude protein was determined as nitrogen using a Kjeldahl analyser (KjeltechTM 2300; FOSS Tecator, Höganäs, Sweden).

2.5.3 Total Carotenoid Content (TCC)

Extraction of carotenoids from spray-dried papaya powder was carried out as reported by Saha and Jindal (2018) with modifications. Approximately 0.1 g of powder was weighed in a stoppered conical flask and extracted with 10 mL of solvent (n-hexane:acetone, 3:2 v/v). Extraction was carried out with continuous stirring on a magnetic stirrer until the powder turned colourless, using 5 mL of solvent each time. The pooled extracts were washed with 25 mL distilled water

in a separating funnel to remove acetone. A few drops of saturated NaCl solution were added to facilitate phase separation. The upper layer was collected for total carotenoid content. The extraction was conducted under dim light and analysed within one day. Standard carotene solutions (0.0005-0.01 mg/mL) were prepared to construct a standard curve. TCC of the spray-dried powder was determined spectrophotometrically at 473 nm and expressed as carotene equivalents (mg/g of powder).

2.5.4 Colour Measurement
The colour of the powder was measured using a colour reader (CR-10; Konica Minolta Sensing Americas Ltd., Ramsey, NJ, USA). To obtain the L*, a*, and b* values, the lens of the colour reader was placed on the powder surface. The values were displayed on the LCD screen. Colour differences were compared across samples. Triplicate samples were analysed, and mean and standard error were reported.

2.5.5 Scanning Electron Microscopy
The spray-dried papaya powder was mounted on aluminium stubs with conductive adhesive and coated with gold using a sputter coater. The samples were viewed at ×500 magnification to study surface morphology. All examinations were carried out at 15 kV using a scanning electron microscope (Model 435 VP; Leo Electron Microscopy Ltd., Cambridge, UK).

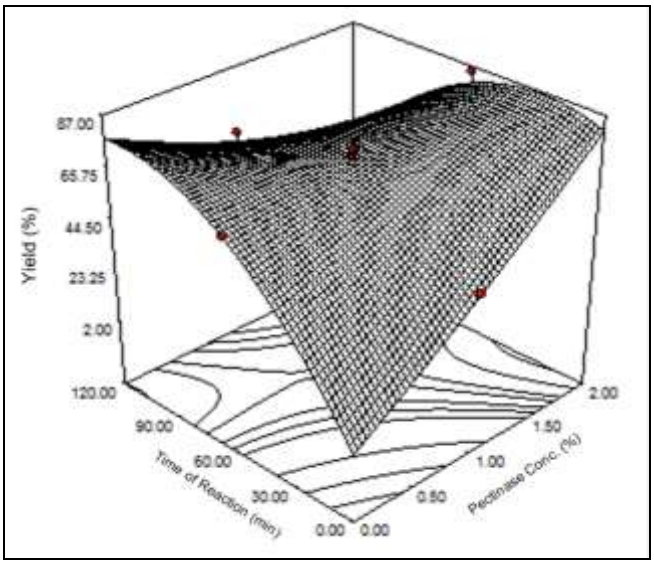
3. Results and Discussion
3.1 Diagnostic Checking of the Model
Three responses were measured in the experiments, namely, yield (Y_1), clarity (Y_2), and TSS (Y_3). The coefficients for the actual functional relationships for predicting Y_1, Y_2, and Y_3 are presented in Table 3. The insignificant terms were omitted based on the Student's t-ratio. The three responses under different combinations as defined in the design (Tables 1 and 2) were analysed using analysis of variance (ANOVA) appropriate to the experimental design. The ANOVA for the data obtained using CCRD is presented in Table 4. It is evident from the data that the first and second order terms were found to be significant, and the lack of fit was not significant. This indicates that the developed regression models adequately represented the experimental data within the design space. The lack of fit measures the failure of the model to represent data at points not included in the regression. The high values of the coefficient of determination (R^2) also suggest that the model is a good fit. A high R^2 reflects that a large proportion of the variability in the experimental data is explained by the fitted model.

Table 2: Treatment schedule for three factor CCRD and the response in terms of yield, clarity, and TSS

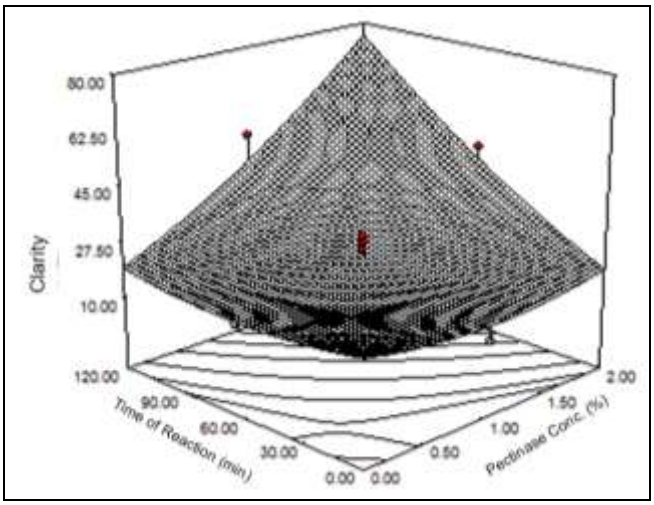
No.	Pectinase conc. (%) (X_1)	Time of reaction (min) (X_2)	Temperature (◦C) (X_3)	Yield (%) (Y1)	Clarity (%T at 660nm) (Y_2)	TSS (◦Brix) (Y_3)
1	-1	-1	-1	43.00	18.40	13.00
2	1	-1	-1	78.00	21.60	13.60
3	-1	1	-1	83.00	20.30	13.50
4	1	1	-1	77.00	40.00	13.70
5	-1	-1	1	46.00	19.20	13.60
6	1	-1	1	72.00	24.80	14.00
7	-1	1	1	63.00	19.80	13.70
8	1	1	1	45.00	49.00	14.70
9	-1.682	0	0	62.00	15.20	13.70
10	1.682	0	0	85.00	48.00	13.70
11	0	-1.682	0	39.60	10.20	13.50
12	0	1.682	0	60.00	51.60	14.30
13	0	0	-1.682	98.00	24.60	14.30
14	0	0	1.682	62.00	26.00	13.80
15	0	0	0	72.00	24.00	14.80
16	0	0	0	70.00	21.00	15.10
17	0	0	0	73.50	26.00	14.50
18	0	0	0	69.00	23.00	15.20
19	0	0	0	68.00	30.00	14.80
20	0	0	0	60.00	28.00	15.00

3.2 Effect of Pectinase Concentration and Reaction Time on Juice Yield
At the optimum level of temperature, an increase in pectinase concentration from 0-2% linearly increased the juice yield. However, when the reaction time increased along with enzyme concentration, the juice yield increased up to a certain level and later decreased significantly (Fig. 2 (a)). It was noted from Table 4 that the linear terms for juice yield were significant ($p \leq 0.05$), the interaction terms were also positively significant ($p \leq 0.05$), and the quadratic terms were negative and non-significant. This pattern indicates an initial improvement in cell-wall degradation followed by a decline at excessive enzyme action or prolonged incubation. Similar findings were reported by Rastogi and Rashmi (1999) [20] for mango pulp, where the linear effect was positive and the quadratic effect negative, producing a curvilinear yield trend across incubation times. Ghosh (2017) [6] also observed that increasing enzyme dosage enhances juice yield by degrading binding pectin-protein complexes. However, Pilnik and Voragen (1993) [18] reported that soft fruits like banana and papaya contain high levels of soluble pectin, and pectinase treatment results in higher juice yield, which aligns with the present findings.

Thus, the interaction between pectinase concentration and incubation time significantly ($p \leq 0.05$) influenced juice yield, indicating the importance of balancing hydrolysis intensity with processing time. The coefficient of determination (R^2) was 0.9398 (Table 4), implying that 93% of data variability was explained by the model. Under the optimised conditions of 1.25% pectinase concentration and 79.33 min reaction time, 78.79% juice yield was obtained (Table 5), which was close to the predicted value of 80.56%. Pilnik and Voragen (1993) [18] reported that enzymatic maceration of papaya and banana yields 60-95 mL of juice per 100 g of material, consistent with the values observed under the present optimised conditions.



(a)



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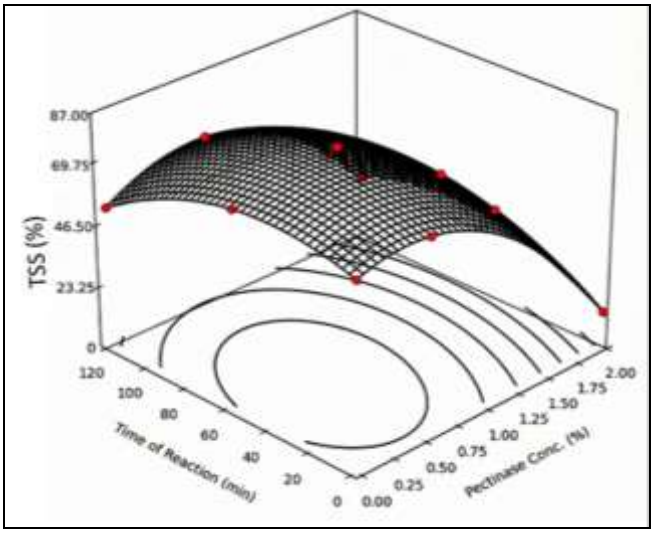


(c)

Fig 2: Response surfaces showing effect of pectinase concentration and time of reaction on (a) yield (b) Clarity (c) TSS

3.3 Effect of Pectinase Concentration and Reaction Time on Juice Clarity

At the lowest levels of reaction time and pectinase concentration, the clarity of the juice increased slowly (Fig. 2 (b)). With a gradual increase in both variables, the clarity increased significantly ($p \leq 0.05$, $p \leq 0.01$). Table 3 shows that reaction time and enzyme concentration were positively significant ($p \leq 0.05$, $p \leq 0.01$) for the linear terms, confirming the trend observed in Fig. 2 (b). However, the quadratic and cross-product terms were non-significant except for the interaction between pectinase concentration and reaction time, which was the only significant interaction ($p \leq 0.05$) (Table 4). This indicates that clarity is primarily governed by the synergistic action of enzyme dosage and incubation duration rather than curvature effects.

From Table 3, the clarity of papaya juice ranged from 10.20% to 51.60% transmittance. The coefficient of determination (R^2) was 0.8941 (Table 4), explaining 89% of data variability. Under the optimised conditions (1.25% pectinase concentration, 79.33 min reaction time), a clarity value of 38.70% transmittance was obtained (Table 5). Increasing pectinase concentration and incubation time enhances the breakdown of pectin molecules, reducing cloudiness and facilitating the formation of pectin-protein flocs that settle out, leaving a clearer supernatant.

This behaviour is consistent with previous reports. Vijayanand *et al.* (2010) [29] observed improved clarity in litchi juice with increased enzyme concentration. Surajbhan *et al.* (2012) [26] described how pectinase breaks down pectin, promoting the removal of colloidal material. Since absorbance and transmittance are inversely related, higher transmittance indicates clearer juice. Abdullah *et al.* (2007) [1] also observed decreasing absorbance with increasing enzyme concentration and incubation time. The present findings reinforce that controlled enzymatic hydrolysis enhances clarity by reducing suspended solids and colloidal particles.

Table 3: Estimated coefficients for the fitted second order polynomial representing the relationship between the response and the process variables

Co-efficient	Yield	Clarity	TSS
a_0	68.89^a	25.43^a	14.90^c
a_1	5.54^b	8.26^a	0.16^d
a_2	4.64^b	8.40^a	0.20^d
a_3	-8.46^a	1.09^d	0.100^d
A_{11}	-10.62^d	5.01^d	0.025^a
a_{22}	-2.62^a	1.49^d	0.075^b
a_{33}	-6.12^c	0.56^d	0.025^b
a_{12}	0.77^a	1.61^c	-0.44^d
a_{13}	-7.61^d	1.36^d	-0.371^d
a_{23}	3.06^c	-0.62^a	-0.32^a

a significant at 0.1%, b significant at 1%, c significant at 5% and d non-significant

Table 4: Analysis of variance (ANOVA) for the fitted second order polynomial model and lack of fit for yield, clarity and TSS as per CCRD

	df	Sum of squares		
		Yield	Clarity	TSS
First-order terms	3	1690.45^a	1912.65^a	1.04^d
Second order terms	3	1258.36^a	221.23^d	0.055^a
Cross product	3	979.123^b	69.64^d	6.35^d
Lack of fit	5	145.57^d	205.74^d	1.01^d
Pure error	5	111.87	55.33	0.32
Total	19	4274.35	2464.91	7.76
R^2		0.9398	0.8941	0.8281

a significant at 0.1%, b significant at 1%, c significant at 5% and d non-significant

3.4 Effect of Pectinase Concentration and Reaction Time on Juice Yield

The combined influence of pectinase concentration and reaction time on juice yield during enzymatic liquefaction of papaya processing waste is illustrated by the response surface plot (Fig. 2c). At lower enzyme concentrations and shorter reaction times, juice yield remained comparatively low, indicating insufficient hydrolysis of pectic substances and incomplete disruption of the cell wall matrix. Under these conditions, the intact pectin-cellulose network restricted juice release, resulting in poor extractability. As pectinase concentration increased from 0 to approximately 1.25%, a marked improvement in juice yield was observed, particularly when accompanied by moderate increases in reaction time. This enhancement can be attributed to effective depolymerization of pectin in the middle lamella and primary cell wall, leading to reduced pulp viscosity, increased cell wall permeability, and improved liquid-solid separation efficiency. Similar trends have been reported for enzyme-assisted liquefaction of soft tropical fruits such as mango and banana, where pectinase treatment significantly enhanced juice recovery by facilitating cellular disintegration (Rastogi & Rashmi, 1999; Pilnik & Voragen, 1993) [20, 18].

However, beyond the optimum region, further increases in pectinase concentration combined with prolonged reaction time resulted in a decline in juice yield. Excessive enzymatic action may cause over-solubilization of structural polysaccharides, generating fine colloidal particles that remain suspended in the liquid phase and hinder efficient filtration. Such colloidal fines can increase juice turbidity and retain moisture within the pomace, thereby reducing the recoverable juice fraction. Similar yield reductions at extended incubation periods have been documented in enzymatic extraction studies of fruit pulps and are often associated with over-hydrolysis and secondary aggregation phenomena.

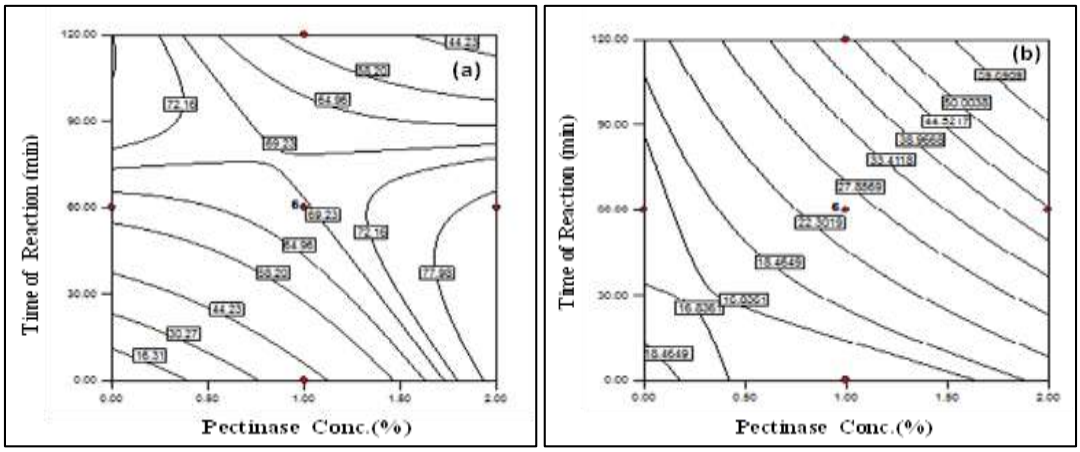
Statistical analysis supports these observations. The linear effects of pectinase concentration and reaction time on juice yield were significant ($p \leq 0.05$), while the quadratic terms exhibited a negative influence, confirming the presence of a maximum yield point rather than a continuously increasing trend. The interaction term between pectinase concentration and reaction time was also significant ($p \leq 0.05$), indicating that the effect of enzyme dosage on yield is strongly dependent on the duration of enzymatic treatment. The high coefficient of determination ($R^2 = 0.9398$) demonstrates that the developed model adequately describes the relationship between the processing variables and juice yield. Under the optimized conditions of 1.25% pectinase concentration and 79.33 min reaction time at approximately 50 °C, a maximum juice yield of 82.79±2.27% was achieved, closely matching the predicted value of 80.56%. These results fall within the range reported for enzymatic liquefaction of soft fruits (60-95%), confirming the effectiveness of controlled enzyme-assisted processing for maximizing juice recovery from papaya processing waste.

3.5 Optimisation

Table 5: Feasible optimum conditions and predicted and experimental value of response at optimum condition

Optimum conditions	Coded levels		Actual Levels
Pectinase	0.84		1.25%
Time of Reaction	0.54		79.33min
Temperature	-0.69		47.22 °C
Responses	Predicted values	Experimental values	
		Mean	Range
Yield (%)	80.56	82.79±2.27	67.88-93.23
Clarity (%T)	38.70	39.00±2.28	25.92-51.46
TSS(◦Brix)	14.46	14.70±0.16	13.55-15.37

The optimisation of independent variables was carried out using the desirability function to obtain maximum juice yield, improved clarity, and higher TSS. The criteria selected for numerical optimisation were: (i) enzyme concentration in the range of 0-2%, (ii) reaction time between 30-120 min, and (iii) temperature between 25-100 °C, while the responses yield, clarity, and TSS were set to be maximised. The software generated an optimised combination of variables with high desirability, indicating a satisfactory compromise between all responses. Under these optimised conditions, the yield, clarity, and TSS values obtained experimentally matched closely with the predicted ones, confirming the validity of the optimisation procedure. The optimum values were found to be 1.25% pectinase concentration, 79.33 min reaction time, and 50 °C temperature. These conditions reflect the balance between adequate enzymatic hydrolysis and the avoidance of excessive viscosity reduction or thermal denaturation effects. The desirability plots and contour overlays demonstrated that optimal clarity and yield occurred at mid-range enzyme concentrations and longer reaction times. Such multi-response optimisation ensures that no single parameter is maximised at the expense of others, maintaining both functional and processing quality.



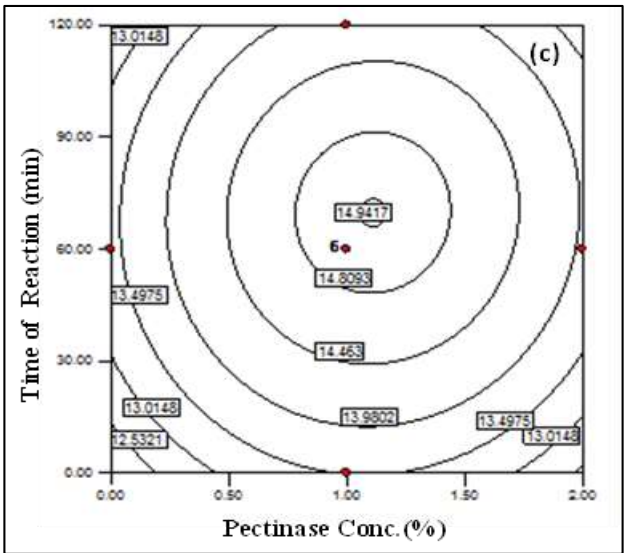


Fig 3: Contour plots showing effect of pectinase concentration and time of reaction on (a) yield, (b) clarity and (c) TSS

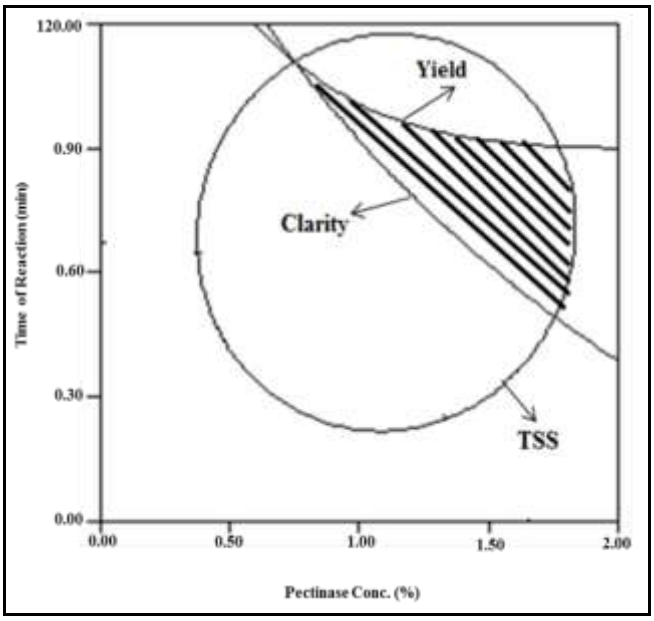


Fig 4: Superimposed contour plots showing the shaded overlapping area for which yield ≥80.55, clarity ≥38.69 and ≥14.46

3.6 Spray drying using optimized parameters

Spray drying of the enzymatically liquefied papaya waste juice was carried out under optimized liquefaction conditions (1.25% pectinase, 79.33 min, ~50 °C), using 20% (w/w) maltodextrin as a carrier and inlet/outlet air temperatures of 120/83 °C. The successful conversion of the liquefied juice into a free-flowing powder (Fig. 5) demonstrates the suitability of spray drying for stabilizing papaya processing waste into a value-added ingredient.

The addition of maltodextrin played a critical role in improving drying performance by reducing stickiness, lowering hygroscopicity, and increasing the glass transition temperature of the feed material. Fruit juices rich in low-molecular-weight sugars and organic acids tend to adhere to dryer walls during spray drying due to their low glass transition temperatures; the incorporation of maltodextrin mitigates this effect by diluting sugars and forming an amorphous protective matrix. Similar strategies have been widely reported for spray drying of tropical fruit juices such as mango, papaya, and guava (Kha *et al.*, 2010; Wong & Lim, 2016) [12, 32].

The selected inlet temperature (120 °C) ensured rapid moisture evaporation while limiting thermal degradation of heat-sensitive bioactive compounds. Rapid crust formation at the droplet surface during spray drying reduces internal diffusion of oxygen, thereby helping to preserve pigments and antioxidants. The outlet temperature of 83 °C further indicates efficient moisture removal without excessive thermal exposure, which is critical for retaining nutritional quality in fruit-based powders (George *et al.*, 2004) [5]. The optimized spray-drying conditions resulted in a stable, visually uniform powder with acceptable handling properties, demonstrating the technical feasibility of converting papaya processing waste into a shelf-stable functional powder suitable for food applications.

Fig 5: Spray dried papaya powder

3.7 Characterization studies of spray dried papaya powder

Table 6: Moisture, proximate principles and colour values for papaya pulp, papaya juice and spray dried papaya powder

Parameters	Papaya pulp	Papaya juice	Spray dried papaya powder
Moisture g/100 g	86.96	86.96	5.49
Proximate principles			
Total Ash g/100 g	0.75[a]	0.60[a]	13.00[b]
Protein g/100 g	3.43[a]	0.17[b]	1.16[a]
Fat g/100 g	0.12[a]	0.00[a]	0.15[a]
Carbohydrates g/100 g	9.08[a]	12.27[a]	80.2[b]
Energy g/100 g	49.79[a]	49.79[a]	326.8[b]
Colour values			
L*	36.19[a]	46.27[b]	88.04[c]
a*	28.45[a]	32.81[a]	4.70[b]
b*	33.93[a]	73.77[b]	20.08[c]
ΔE	75.77[a]	95.89[b]	23.56[c]

3.7.1 Moisture content

The spray-dried papaya powder exhibited a moisture content of 5.49 g/100 g, which is substantially lower than that of papaya pulp and juice (86.96 g/100 g). This low residual moisture is desirable for enhanced shelf life, as moisture levels below 6% significantly reduce microbial growth and slow chemical degradation reactions such as lipid oxidation and enzymatic browning. Spray drying is particularly effective in producing low-moisture powders because of the large surface area generated during atomization and the short residence time of droplets in the drying chamber. Comparable moisture values have been reported for spray-dried papaya and mango powders prepared using maltodextrin as a carrier (Kha *et al.*, 2010; Gomes *et al.*, 2018) [12, 7], confirming that the present drying conditions were adequate for producing a microbiologically stable product.

3.7.2 Proximate analysis

The proximate composition of the spray-dried papaya powder revealed a marked increase in carbohydrate content (80.2 g/100 g) and energy value (326.8 kcal/100 g) compared to pulp and juice. This increase is primarily attributable to the concentration effect caused by moisture removal and the addition of maltodextrin, which is a carbohydrate-rich drying aid. Ash content increased significantly in the powder (13.0 g/100 g), indicating concentration of mineral constituents during dehydration. Similar increases in ash content following spray drying have been reported for fruit powders and are commonly associated with moisture reduction rather than absolute mineral enrichment (Kha *et al.*, 2010) [12]. Protein and fat contents were relatively low in the powder, which is consistent with the intrinsic composition of papaya and dilution by maltodextrin. Enzymatic liquefaction and filtration steps are also known to reduce protein levels due to removal of insoluble solids. Overall, the proximate profile suggests that the spray-dried powder is an energy-dense, carbohydrate-rich ingredient with potential applications in functional foods and nutraceutical formulations.

3.7.3 Total carotenoid content

A reduction in total carotenoid content was observed in the spray-dried powder compared to fresh pulp and juice (Fig. 6). This decline can be attributed to thermal degradation and oxidative losses during spray drying, as carotenoids are highly sensitive to heat, light, and oxygen (Rodriguez-Amaya, 2016). Despite these losses, appreciable carotenoid retention was achieved, which can be attributed to the protective effect of maltodextrin. The encapsulating matrix formed during spray drying limits oxygen diffusion and reduces direct exposure of carotenoids to heat, thereby improving their stability (Mishra *et al.*, 2014; Saha & Jindal, 2018) [16, 23]. Similar retention trends have been reported for spray-dried papaya and carrot powders, confirming that controlled spray-drying conditions can preserve a substantial fraction of bioactive compounds (Gomes *et al.*, 2018) [7].

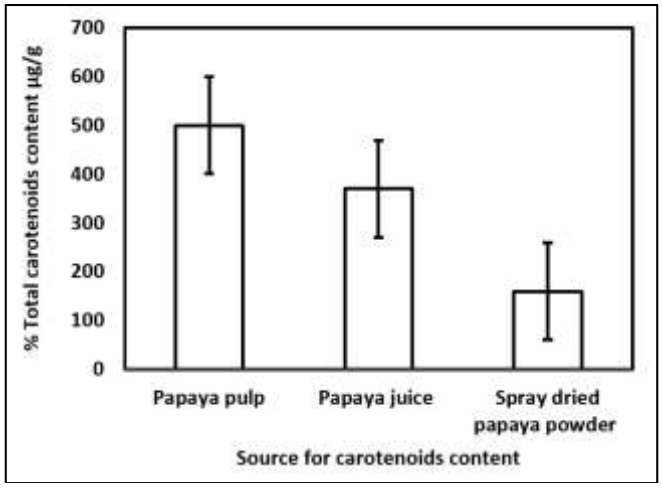


Fig 6: Total carotenoids content in papaya pulp, papaya juice and spray dried papaya powder

3.7.4 Colour

The colour measurements revealed a significant increase in lightness (L*) for the spray-dried powder (88.04) compared to pulp and juice, indicating a lighter appearance. This whitening effect is primarily due to the presence of maltodextrin, which is inherently white and dilutes the natural pigments of papaya (Kha *et al.*, 2010) [12]. The reduction in a* (redness) and b* (yellowness) values in the powder reflects partial degradation and dilution of carotenoid pigments during drying. Nevertheless, the retention of positive a* and b* values indicates that the characteristic colour of papaya was largely preserved.

Similar colour trends have been reported for spray-dried tropical fruit powders and are considered acceptable for food applications where reconstitution or blending is intended (Gomes *et al.*, 2018; Wong & Lim, 2016) [7, 32].

3.7.5 Scanning electron microscopy

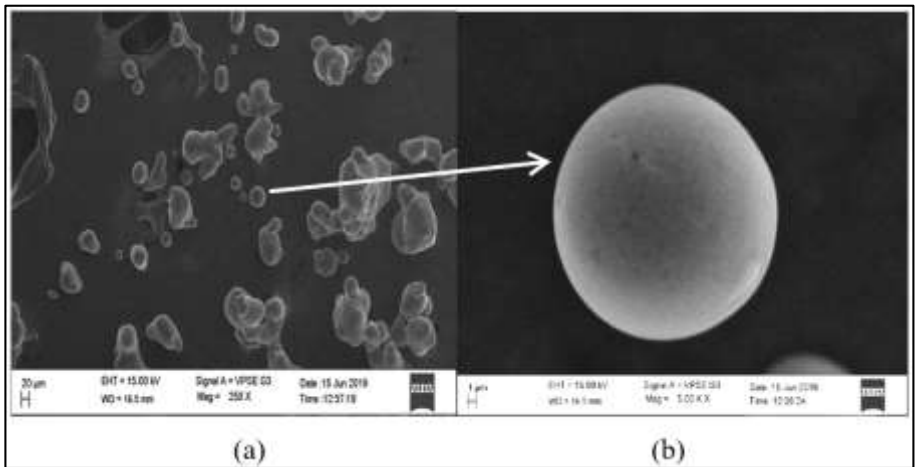


Fig 7: Scanning Electron Microscope of Spray dried papaya powder (20% Maltodextrin, 120/83◦C inlet/outlet temperature) (a). Papaya Powder 250X and (b) at 5.00K X magnification

Scanning electron micrographs of the spray-dried papaya powder showed predominantly spherical particles with smooth to slightly wrinkled surfaces. Such morphology is characteristic of maltodextrin-based spray-dried powders and results from rapid moisture evaporation followed by particle wall collapse during drying (Walton, 2000) [31]. The absence of large agglomerates indicates effective atomization and appropriate drying conditions, which contribute to good flowability and dispersibility of the powder. Slight surface indentations observed on some particles are typical of carbohydrate-rich systems and are associated with internal vapor pressure changes during drying. The observed morphology suggests efficient encapsulation of juice solids, which can enhance the stability of sensitive components such as carotenoids and flavour compounds.

4. Conclusion

The present investigation successfully demonstrated the conversion of papaya processing waste into a stable, value-added functional powder through optimized enzymatic liquefaction and spray drying. Response surface methodology proved to be an effective tool for optimizing the enzymatic liquefaction process, revealing that pectinase concentration, reaction time, and temperature significantly influenced juice yield, clarity, and TSS. The optimized liquefaction conditions (1.25% pectinase, 79.33 min, ~50 °C) resulted in high juice recovery with improved clarity and soluble solids, validating the robustness and predictive capability of the developed models. Spray drying of the optimized juice using maltodextrin as a carrier yielded a low-moisture, free-flowing powder with desirable physicochemical and morphological properties. The reduction in moisture content substantially enhances shelf life, while the retention of carotenoids and acceptable colour characteristics indicate preservation of nutritional and functional quality. Scanning electron microscopy confirmed the formation of predominantly spherical particles with minimal agglomeration, suggesting good flowability and reconstitution behaviour. Overall, this study establishes a technically feasible and sustainable route for the valorisation of papaya processing waste into a functional food ingredient. The integrated approach not only mitigates waste disposal issues but also adds economic value by generating a nutritionally enriched powder with potential applications in food and nutraceutical formulations. The findings support the broader adoption of enzymatic processing and spray drying as effective strategies for fruit waste utilization within a circular economy framework.

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