



Tradition Meets Technology: Optimizing Paneer with Reverse Centrifugal Expulsion

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ABSTRACT

Background: *Paneer* is traditionally produced by acid coagulation of milk followed by manual pressing, a method that is labour-intensive, inconsistent and susceptible to nutrient losses. To overcome these limitations, the present study explores a reverse centrifugal expulsion approach as a hygienic and mechanized alternative for whey removal and paneer formation.

Methods: A semi-automatic reverse centrifugal expulsion prototype integrating a controlled and insulated heated processing vessel with agitator, controlled acid dosing unit and centrifugal pressing assembly was developed. The effects of coagulation temperature (70–80°C, 3 levels), rotation speed (235.3–289.6 RPM, 4 levels) and pressing time (3–5 min, 3 levels) on *paneer* yield and composition were investigated using an I-optimal response surface design with 30 runs. Statistical modelling and numerical optimization were performed to maximise product yield using Design Expert 13.0.5.0 software and analyse process-response relationships.

Result: Coagulation temperature and rotation speed significantly influenced *paneer* yield, moisture, fat and total solids ($p < 0.01$), whereas pressing time had a limited effect. Higher temperatures and speeds reduced yield and moisture but improved fat and solids retention due to compact curd structure. The models showed strong predictive accuracy ($R^2 > 0.86$) with non-significant lack of fit. Optimal conditions (70°C, 235.3 RPM, 3 min) achieved maximum yield with high reproducibility (desirability = 0.962), demonstrating the method's industrial potential.

Key words: Coagulation temperature, Dairy process automation, *Paneer* manufacturing, Process optimization, Response surface methodology (RSM), Reverse centrifugal expulsion.

INTRODUCTION

In recent decades, the demand for fresh acid-coagulated dairy products such as *paneer* has grown markedly, driven by consumer preferences for traditional foods with high protein content and minimal processing (Khan *et al.*, 2011; Prajapati *et al.*, 2023). *Paneer* is typically produced by coagulating heated milk using food-grade acids (e.g. citric, lactic) followed by separation of whey and pressing of the curd. However, efficient separation of whey from curd without undue loss of protein, fat, or moisture remains a technical challenge, especially when scaling up processes or ensuring consistency in yield and composition (Kumar and Singh, 2024).

A number of investigators have studied the effects of coagulation temperature, coagulant concentration, pressing time and mechanical pressure on *paneer* yield and quality (Singh *et al.*, 2015; Alam *et al.*, 2024). For instance, Singh *et al.* (2015) optimized coagulation temperature and ingredient levels to improve texture and yield, while Alam *et al.* (2024) reviewed the complex interplay between milk variety, coagulant type and pretreatments in determining yield and quality.

Increasing coagulation temperature tends to yield a denser and stiffer curd structure, which may reduce syneresis or whey expulsion, but can also promote heat-induced denaturation and lower moisture retention (Laursen *et al.*, 2023). Conversely, lower coagulation temperatures often favour a more open protein network that may trap more moisture but risk higher losses during

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pressing and whey draining (Ong *et al.*, 2011). The balance of these effects is delicate and depends on interactions among temperature, curd stirring, acid addition kinetics and mechanical separation forces.

Traditional pressing or drainage methods are limited by the trade-off between yield and texture. Traditional pressing, carried out at low mechanical stress, helps retain moisture-associated nutrients such as whey proteins, water-soluble vitamins and minerals, while preserving the native microstructure of milk proteins, which contributes to better digestibility and sensory quality (Huppertz, 2025). In response, novel separation techniques such as centrifugal

expulsion have been explored in dairy processing for whey removal and curd consolidation (Croguennec *et al.*, 2024). While high-speed centrifugation has been applied in milk component separation (e.g. cream skimming, spore removal) (D'Incecco *et al.*, 2020), adapting centrifugal approaches to *paneer* or acid-coagulated curd systems is less common. Studies indicate that controlled centrifugal separation can achieve a balance between nutritional retention and yield enhancement, offering improved compositional uniformity without significant degradation of protein quality. Therefore, integrating principles of traditional pressing with optimized centrifugal action can support the production of nutritionally rich, hygienic and consistent *paneer* suitable for modern dairy processing (Kumar, 2022).

A "reverse centrifugal" expulsion mechanism-where whey is forced outward from a curd matrix under controlled agitation and rotation-offers promise in reducing whey losses while applying more uniform mechanical pressure to the curd. In designing such a system, key parameters such as coagulation temperature, stirring/agitation conditions, centrifugal speed and pressing duration require systematic optimization. Statistical design of experiments, particularly response surface methodology (RSM) or I-optimal designs with point exchange have proven valuable in dairy product process optimization (e.g. Bidasagar *et al.*, 2023; Walsh *et al.*, 2024). These designs allow modelling of linear, interaction and non-linear effects of process variables and enable prediction of optimal operating conditions.

Given this backdrop, this work presents a semi-automatic reverse centrifugal prototype tailored to *paneer* manufacture from buffalo milk. The objective was to systematically investigate the influence of coagulation temperature, centrifugal speed and pressing time on *paneer* yield and composition and to develop predictive models to guide process optimization. Presented approach combines controlled lab-scale prototype with rigorous statistical design and standard physico-chemical characterization.

MATERIALS AND METHODS

A semi-automatic reverse centrifugal prototype consisting of a double jacketed insulated processing vessel with an agitator and acid dosing unit was used. As full fat milk is suggested for firm *paneer* (Suthar *et al.*, 2018), Standardized buffalo milk (Fat:SNF::1:1.65) was heated to 82°C, held for 5 minutes and then cooled to the desired coagulation temperature (70, 75, or 80°C). A 1% (% w/v) citric acid solution, preheated to the same temperature, was added while continuous stirring until whey separation was prominently visible. The stirrer was then replaced with the centrifugal pressing assembly lined with muslin cloth and the separated whey was drained and collected. Centrifugal pressing was carried out at different rotation speeds (235.3 to 289.6 RPM) and pressing times (3 to 5 minutes). After pressing, the coagulum was removed and

weighed. Coagulum was cut into 2.5 cm *paneer* cubes and stored in refrigerated conditions submerged in chilled brine (10% w/v sodium chloride in distilled water). All experiments were conducted during year 2025 at Dairy Engineering Division, ICAR-National Dairy Research Institute, Karnal.

The physico-chemical properties of *paneer* were analysed using standard FSSAI methods (FSSAI, 2022). The moisture content of *paneer* was estimated following the FSSAI 01.043:2022 method, while fat content was analysed using FSSAI 01.044:2022 (FSSAI, 2022). Total solids (TS) were calculated by subtracting moisture content from 100 and solids-not-fat (SNF_f) was derived by subtracting fat content from total solids. *Paneer* yield (% by weight of milk) was also recorded for each trial. Results are presented in Table 1.

Statistical analyses

A total of 30 experimental trials (Table 1) were carried out in random order using an I-optimal design with point exchange (Walsh *et al.*, 2024), created in Design Expert 13.0.5.0 software (Stat-Ease, 2021). The design included ten required model points, five additional model points, ten lack-of-fit points and five replicate points to ensure accuracy. In experimental setup, coagulation temperature was tested at three levels (70, 75 and 80°C), rotation speed was adjusted with a variable frequency drive to four levels (235.3, 253.4, 271.5 and 289.6 RPM) and pressing time was tested at three levels (3, 4 and 5 minutes). Data were analysed using Microsoft Excel (Microsoft Corporation, 2013), Design Expert and R Studio (R Core Team, 2025). Microsoft Excel was used for data tabulation and optimal parameter validation using paired t-test. Design Expert was used for design of experiment, Analysis of variance (ANOVA), regression analyses, numerical optimisation, 3-D surface plots, R studio was used for creation of heat-map and correlation analyses. ANOVA (Table 2) was used to check the effect of each factor, regression analysis (Table 3, Fig 1) was applied to fit the best model and correlation analysis (Fig 2) was performed to study relationships among the factors and responses.

Response surface plots were prepared (Fig 1) and the data were optimized using Design Expert 13.0.5.0 software to find the best conditions (criteria in Table 4). The optimized experiments were repeated three times. Student's t-test ($p < 0.05$) was used to check if the experimental results were significantly different from the predicted values. R_d values were calculated using Equation (1) (Lamauro *et al.*, 1985).

$$R_d = \frac{100}{n} \sum_{i=1}^n \left| \frac{Q_{iexp} - Q_{ipre}}{Q_{iexp}} \right| \quad \dots(1)$$

Where,

R_d = Relative deviation per cent.

Q_{iexp} = Experimental value of response.

Q_{ipre} = Predicted value of response.

RESULTS AND DISCUSSION

The effect of different factors on responses was analysed using ANOVA (Table 2), regression (Table 3), response surface plots (Fig 1) and correlation analysis (Fig 2).

Paneer yield was found to be varying from 18.90 to 22.24% ($20.72 \pm 0.95\%$) whereas its SNF (% w.b.), Fat (% w.b.), Moisture (% w.b.) and Total Solids (% w.b.) varied from 21.77 to 23.81% ($22.77 \pm 0.61\%$), 25.17 to 28.44% ($26.66 \pm 0.97\%$), 49.23 to 51.57% ($50.56 \pm 0.60\%$) and 48.43 to 50.70% ($49.44 \pm 0.60\%$) respectively during the experimental trials (Table 1).

ANOVA (Table 2) showed that yield and SNF (% w.b.) were significantly ($p < 0.01$) affected by coagulation temperature and speed of rotation and not affected by pressing time; whereas Fat (% w.b.), Moisture (% w.b.) and Total Solids (% w.b.) were significantly affected by all three parameters. All non-significant terms were removed from the model and model was reduced to

modified linear model as indicated in Table 2. A non-significant lack of fit for all affected parameters indicated that the model was acceptable to carry on further statistical analysis (Table 2).

Regression analysis was performed on modified linear model to get coefficients of intercept and linear term for all studied parameters and tabulated in Table 3.

Coefficient of determination (R^2) of various parameters studied ranged from 0.8644 to 0.9926 indicating that fitted model was able to explain more than 86% of variation for each parameter under study. The Predicted R^2 values were also observed is in reasonable agreement with the Adjusted R^2 value as the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. All the studied parameters demonstrated ratio of greater than 24 indicating an adequate signal. Hence it could be inferred that the fitted models can be used to navigate the design space (Table 3).

Table 1: Experimental design and data for the response surface analysis using I-optimal design.

Coagulation temperature (°C)	Rotation speed (RPM)	Pressing time (min)	Yield (%)	SNF (% w.b.)	Fat (% w.b.)	Moisture (% w.b.)	Total solids (% w.b.)
70	235.3	4	21.82	23.27	25.19	51.54	48.46
75	235.3	5	20.88	22.66	26.28	51.06	48.94
80	235.3	5	20.35	21.86	27.41	50.73	49.27
70	253.4	3	22.07	23.41	25.36	51.23	48.77
75	289.6	4	20.35	23.12	26.96	49.92	50.08
75	271.5	3	20.10	22.86	26.80	50.34	49.66
75	235.3	4	21.32	22.58	26.20	51.22	48.78
70	289.6	3	21.68	23.74	25.82	50.44	49.56
75	289.6	4	20.65	22.94	27.06	50.01	49.99
80	235.3	4	19.55	21.77	27.50	50.74	49.26
75	289.6	3	20.72	23.10	26.96	49.94	50.06
80	271.5	3	20.02	22.12	27.86	50.02	49.98
70	289.6	5	20.68	23.81	26.09	50.10	49.90
75	271.5	5	20.89	22.95	26.74	50.31	49.69
80	271.5	4	19.10	22.16	28.15	49.69	50.31
70	235.3	3	22.24	23.27	25.17	51.57	48.43
70	235.3	5	22.16	23.33	25.27	51.40	48.60
80	289.6	3	19.46	22.29	28.15	49.56	50.44
80	253.4	3	19.81	21.98	27.65	50.37	49.63
70	271.5	3	21.89	23.57	25.58	50.85	49.15
80	289.6	5	18.90	22.34	28.44	49.23	50.77
70	253.4	4	22.06	23.41	25.38	51.21	48.79
75	253.4	4	21.11	22.78	26.47	50.75	49.25
80	235.3	3	20.04	21.78	27.33	50.89	49.11
75	271.5	5	19.98	22.76	26.95	50.29	49.71
75	253.4	3	20.23	22.75	26.62	50.63	49.37
75	253.4	4	20.68	22.60	26.53	50.87	49.13
80	271.5	4	20.00	21.90	27.88	50.23	49.77
70	271.5	4	21.84	23.61	25.63	50.76	49.24
75	253.4	4	21.01	22.52	26.45	51.04	48.97

% w.b.: Per cent wet basis.

Table 2: Analysis of variance for various parameters on modified linear model for response surface analysis using I-optimal design.

Parameter	Source	Model	Coagulation temperature (°C)	Rotation speed (RPM)	Pressing time (min)	Residual	Lack of fit	Pure error	Cor total
Yield (%)	df	2	1	1		27	22	5	29
	SS	22.54	20	2.02		3.53	2.57	0.9666	26.08
	MSS	11.27	20	2.02		0.131	0.1167	0.1933	
	F	86.09	152.8	15.39			0.6038		
	p	<0.0001	<0.0001	5 × 10 ⁻⁴			0.8129		
Fat (% w.b.)	df	3	1	1	1	26	21	5	29
	SS	26.82	23.56	2.6	0.0676	0.201	0.1346	0.0663	27.02
	MSS	8.94	23.56	2.6	0.0676	0.008	0.0064	0.0133	
	F	1157	3049.99	336.4	8.75		0.4837		
	p	<0.0001	<0.0001	<0.0001	0.0065		0.8898		
SNF (% w.b.)	df	2	1	1		27	22	5	29
	SS	10.69	9.96	0.952		0.177	0.0699	0.1066	10.86
	MSS	5.34	9.96	0.952		0.007	0.0032	0.0213	
	F	817.5	1523.3	145.6			0.1492		
	p	<0.0001	<0.0001	<0.0001			0.9994		
Total solids (% w.b.)	df	3	1	1	1	26	21	5	29
	SS	9.96	2.88	6.71	0.1051	0.396	0.2073	0.1887	10.35
	MSS	3.32	2.88	6.71	0.1051	0.015	0.0099	0.0377	
	F	217.9	189.39	440.3	6.9		0.2617		
	p	<0.0001	<0.0001	<0.0001	0.0142		0.9872		
Moisture (% w.b.)	df	3	1	1	1	26	21	5	29
	SS	9.96	2.88	6.71	0.1051	0.396	0.2073	0.1887	10.35
	MSS	3.32	2.88	6.71	0.1051	0.015	0.0099	0.0377	
	F	217.9	189.39	440.3	6.9		0.2617		
	p	<0.0001	<0.0001	<0.0001	0.0142		0.9872		

df: Degree of freedom; SS: Sum of squares; MSS: Mean sum of squares; F: Ratio of variances; p: Probability; % w.b.: Per cent wet basis.

It was observed that yield, SNF and moisture decreased significantly with higher coagulation temperature, while fat and total solids increased significantly. Higher rotation speed increased fat, SNF and total solids but reduced yield and moisture. Pressing time

had minor effects: fat and total solids increased, moisture decreased and yield and SNF were largely unaffected (Table 3, Fig 1).

As *paneer* is a high moisture freshly coagulated milk protein gel, it could be compared with fresh cheese.

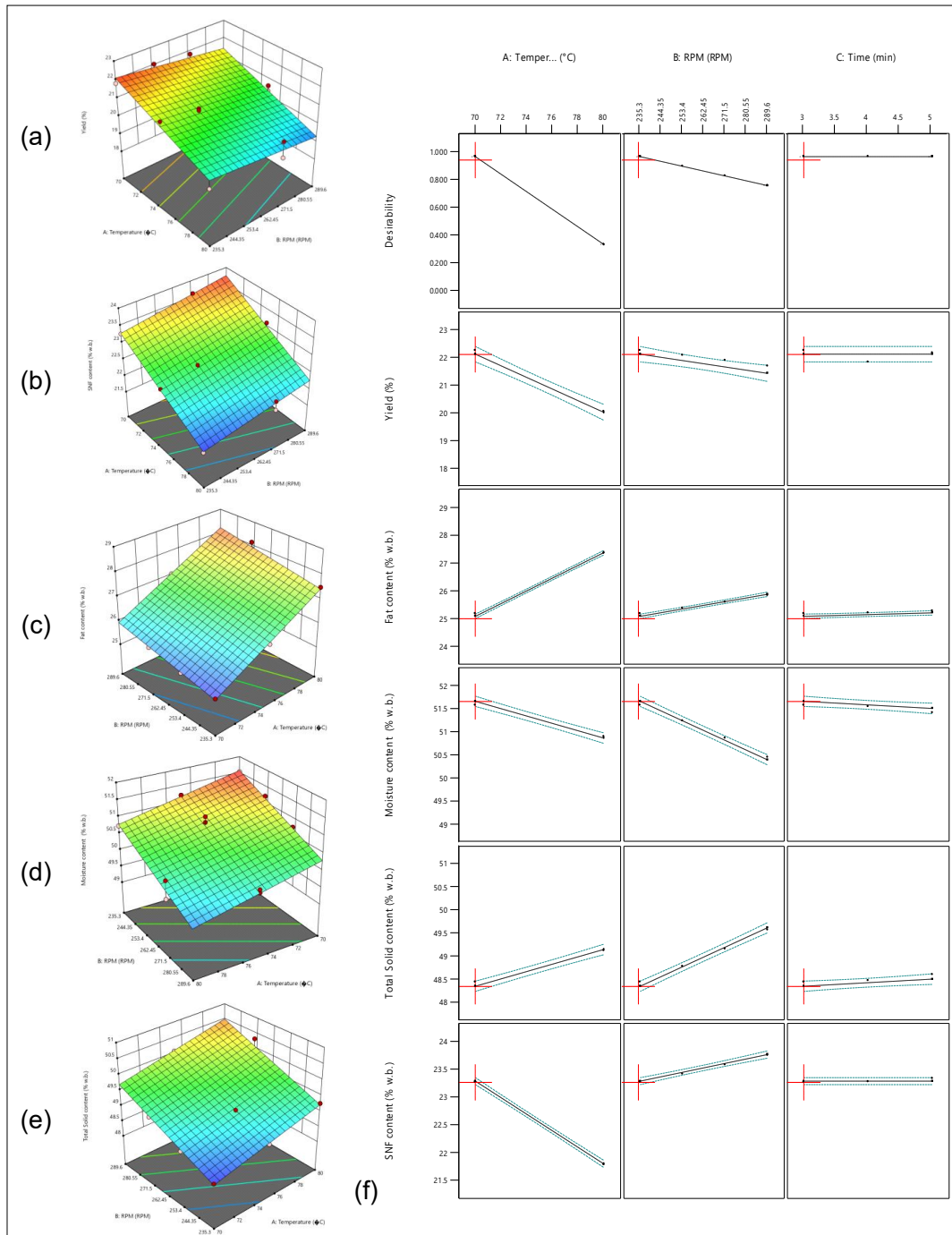


Fig 1: Response surface and contour plots of (a) Yield (%), (b) SNF (% w.b.), (c) Fat (% w.b.), (d) Moisture (% w.b.), (e) Total Solids (% w.b.) as influenced by level of Coagulation temperature and Rotation speed and (f) variation in desirability and responses influenced by single factors during pressing step by reverse centrifugal expulsion technique for response surface analysis of fitted modified linear model using I-optimal design.

Ong *et al.* (2011), studied influence of coagulation temperatures on composition, yield and texture of cheese. It was reported that at lower coagulation temperatures, the cheese curd formed a smooth, connected protein network, while at higher temperatures; the structure became coarse, irregular and less continuous. This suggests that higher temperatures may cause more solids to be lost from the curd into the whey. Decrease in temperature increases moisture retention was also reported by many researchers (Arvind *et al.*, 2019; Tellabati *et al.*, 2023; Sinha *et al.*, 2021) which strengthens finding of present work.

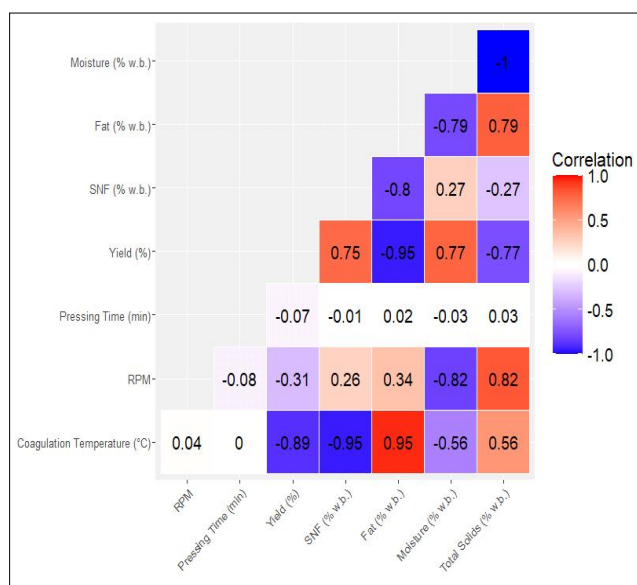


Fig 2: Correlation heat map of various parameters under study for *paneer* making using reverse centrifugal expulsion technique for response surface analysis of fitted modified linear model using I-optimal design.

The correlation heat-map (Fig 2) highlights how process parameters affect *paneer* quality. Coagulation temperature was the most influential factor, strongly negatively correlated with yield (-0.95) and SNF (-0.89), positively correlated with fat (0.95) and moderately negatively correlated with moisture (-0.56), indicating higher temperatures reduce yield and moisture but increase fat retention. Rotation speed (RPM) moderately affected *paneer*, strongly reducing moisture (-0.82) and increasing total solids (0.82), enhancing compactness. Yield is strongly positively correlated with *paneer* SNF (0.75) but strongly negatively correlated with *paneer* fat retention (-0.95). This suggests that retaining non-fat solids is key for yield, while fat retention (though desirable for nutritional value) may inversely relate to the amount of curd produced per litre of milk in the configuration studied. Pressing time had negligible impact, while moisture and total solids showed a perfect negative correlation (-1.0). Overall, coagulation temperature governs yield and composition, rotation speed adjusts texture and pressing time plays a minor role.

Table 4 shows the limits, criteria for optimization and the predicted and actual results. The goal of optimization was to maximize *paneer* yield. The best conditions were found to be a coagulation temperature of 70°C, rotation speed of 235.3 RPM and pressing time of 3 minutes, with a desirability of 0.962 (Fig 1f). Report by Chaudhari *et al.* (2022) also confirms coagulation temperature of 70°C yield better *paneer*. The criteria used for numerical optimisation was aimed at minimising TS loss in whey while maximising *paneer* yield. Experimental results were compared with predicted ones using a student's t-test and no significant difference was found at the 5% level. The % R_d value was below 10, showing that experimental and predicted results matched well. This confirms that the response surface optimization model was reliable.

Table 3: Regression coefficients and other statistical parameters of fitted modified linear model for response surface analysis using I-optimal design.

Particulars	Yield (%)	SNF (% w.b.)	Fat (% w.b.)	Moisture (% w.b.)	Total solids (% w.b.)
Intercept	39.9024 ^{ns}	31.6313 ^{ns}	5.4198 ^{ns}	63.0205 ^{ns}	36.9795 ^{ns}
Coagulation temperature (°C)	-0.2110**	-0.1489**	0.2290**	-0.0801**	0.0801**
Rotation speed (RPM)	-0.0128**	0.0088**	0.0146**	-0.0235**	0.0235**
Pressing time (min)	NA	NA	0.0624**	-0.0779*	0.0779*
Mean	20.72	22.77	26.66	50.56	49.44
Std. dev.	0.3618	0.0809	0.0879	0.1234	0.1234
C.V. %	1.7500	0.3550	0.3297	0.2441	0.2496
R ²	0.8644	0.9838	0.9926	0.9618	0.9618
Adjusted R ²	0.8544	0.9826	0.9917	0.9573	0.9573
Predicted R ²	0.8327	0.9808	0.9900	0.9511	0.9511
Adeq precision	24.5258	76.9422	99.9635	49.5200	49.5200

NA: Not applicable; ^{ns}: Not significant; *: Significant at 5% level ($p \leq 0.05$); **: Significant at 1% level ($p \leq 0.01$); Std. dev.: Standard deviation; C.V. %: Per cent coefficient of variation; R²: Coefficient of determination; Adeq precision: Adequate precision.

Table 4: Constraints, criteria for numerical optimization, solution along with predicted and actual response values.

Constraints	Goal	Lower limit	Upper limit	Importance	Solution	Actual response values (n = 3)	% R _d	t value
Coagulation temperature (°C)	in range	70	80	3	70	-	-	-
Rotation speed (RPM)	in range	235.3	289.6	3	235.3	-	-	-
Pressing time (min)	in range	3	5	3	3	-	-	-
Yield (%)	Maximize	18.903	22.244	3	22.115	21.84±0.357	1.687 ^{ns}	1.326 ^{ns}

R_d: Relative deviation percent (equation 1); ^{ns}: Not significant, the predicted values and actual reported values for any response differed non-significantly (p≤0.05); t: Critical two-tail (at 2 degree of freedom) = 4.30265273.

This study establishes a framework for optimizing paneer manufacturing at industrial scale, identifying coagulation temperature and rotation speed as critical parameters influencing yield more effectively than extended pressing time. Moisture retention emerged as the dominant determinant of paneer yield. Future research should investigate the interaction of these parameters with milk composition, starter cultures and enzymatic activity to refine predictive models. The integration of advanced sensors, machine learning and closed-loop automation offers promising avenues for real-time monitoring and precision control, ensuring consistent product quality. Additionally, evaluating the adaptability of the developed system across diverse production environments-from village-level units to large dairies-will validate its modular and scalable design. Expanding its application to sustainable whey management and value addition can further enhance resource efficiency, supporting the transition toward a circular bioeconomy and strengthening the sustainability of the dairy sector.

CONCLUSION

This study effectively showcased the potential of a semi-automatic reverse centrifugal expulsion prototype for *paneer* production, focusing on enhancing yield. The study demonstrated that coagulation temperature, rotation speed (RPM) and pressing time significantly influence *paneer* yield and composition when using a reverse centrifugal expulsion technique. Coagulation temperature was the most critical factor, with higher temperatures reducing yield, SNF and moisture but increasing fat and total solids. Higher rotation speeds improved fat, SNF and total solids while reducing moisture and yield, whereas pressing time had minor effects. Optimization using response surface methodology identified the best conditions for maximum yield as 70°C coagulation temperature, 235.3 RPM and 3 minutes pressing time, with experimental results closely matching predicted values. The developed semi-automatic system shows strong potential for industrial-scale *paneer* production, offering precise control over product physico-chemical characteristics.

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Disclaimers

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Authors' contributions

Ankit Deep: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing-Original Draft, Writing-Review and Editing, Visualization, Project administration; Kamlesh Prasad: Conceptualization, Methodology, Software, Investigation, Resources, Writing-Review and Editing, Visualization, Supervision, Project administration; Navdeep Jindal: Conceptualization, Methodology, Writing-Review and Editing, Supervision, Project Administration.

Informed consent

This study did not require and third person involvement, hence doesn't require any consent from any person.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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