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RESEARCH ARTICLE

Whey forward: Reducing total solids for cleaner effluents and value-added products using reverse centrifugal expulsion

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Abstract: *Paneer* production in India is still dominated by manual pressing, which is labour-intensive, inconsistent, and prone to nutrient loss in whey. To address this challenge, a semi-automatic reverse centrifugal expulsion prototype was utilised, integrating a processing vessel, insulated jacket, agitator, acid dosing unit, centrifugal pressing chamber, and control panel. The system was evaluated using a response surface design with coagulation temperature (70-80 °C), rotation speed (235.3-289.6 RPM), and pressing time (3-5 min) as key variables. Results showed that coagulation temperature was the most significant factor ($p < 0.01$) affecting whey composition and *paneer* yield, while pressing time had negligible influence. Regression models demonstrated high reliability ($R^2 > 0.88$), and experimental validation confirmed good agreement with predicted values ($p < 0.05$). Optimal conditions were identified as 70 °C coagulation temperature, 235.3 RPM, and 3 min pressing, yielding *paneer* with minimal whey nutrient loss. The study confirms that reverse centrifugal expulsion is a cost-effective, energy-efficient, and scalable technology for *paneer* manufacturing, offering small- and medium-scale dairies a sustainable alternative to conventional pressing while simultaneously reducing whey disposal challenges.

Keywords: Reverse centrifugal expulsion, Whey management, Process optimization, Response surface methodology (RSM), Nutrient retention

Introduction

Whey, the liquid by-product generated during the manufacture of cheese, *paneer*, and other dairy products, represents nearly 85-90% of the milk volume and retains 55-70% of the nutrients originally present in milk (Smithers, 2008). It is primarily composed of lactose (4.5-5% w/v), whey proteins (0.6-0.8% w/v), minerals, and bioactive peptides (Smithers, 2008). Whey proteins such as β-lactoglobulin, α-lactalbumin, and immunoglobulins possess high biological value and functional properties, making them desirable in infant nutrition, sports supplements, and functional foods (Pescuma et al. 2010). Its lactose fraction serves as a versatile raw material for lactic acid, ethanol, galacto-oligosaccharides, and other prebiotics (Siso, 1996). Thus, whey is increasingly recognized as a valuable raw material for functional foods, nutraceuticals, beverages, bioethanol, single-cell proteins, and prebiotics.

Despite its nutritional potential, whey is widely regarded as one of the most polluting effluents of the dairy industry. Its high organic load, mainly due to lactose and residual proteins, results in elevated biological oxygen demand (BOD: 30,000-50,000 mg/L) and chemical oxygen demand (COD: 60,000-80,000 mg/L) (Prazeres et al. 2012). Studies report that one litre of untreated whey effluent can contaminate up to 40–50 litres of water (Guimarães et al. 2010). Such disposal leads to oxygen depletion in aquatic ecosystems, threatening aquatic life and making whey management an urgent ecological challenge.

Technologies such as ultrafiltration, nanofiltration, and reverse osmosis have been employed to fractionate whey proteins and lactose. Ultrafiltration, for instance, yields whey protein concentrates (WPC) of 35-80% purity (Morr & Ha, 1993). These technologies are effective but often require high capital investment, significant energy inputs, and skilled operation.

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Whey provides an excellent substrate for microbial fermentation, supporting the production of lactic acid, ethanol, probiotics, and single-cell proteins (Siso, 1996; Panesar et al. 2007). Fermentation is an attractive valorisation pathway, but it is sensitive to substrate variability and requires stringent process controls, which may limit adoption in decentralized dairy units.

Spray drying enables the production of whey powder, widely used in bakery, confectionery, and infant formula industries (Smithers, 2015). However, high energy costs remain a significant barrier to cost-effective application.

Recent studies highlight novel methods such as electrodialysis, enzymatic hydrolysis, and centrifugal expulsion for whey treatment and valorisation (Prazeres et al. 2012). Mechanical separation techniques particularly reverse centrifugal expulsion are being explored as low-energy, scalable alternatives for handling whey solids.

Although membrane and fermentation technologies have demonstrated effectiveness, they are resource-intensive and often impractical for small- and medium-scale enterprises (SMEs). Conventional methods also struggle with issues such as fouling, incomplete solids separation, or high operational costs.

A persistent bottleneck lies in the management of total solids (TS). High TS levels not only elevate treatment costs but also complicate handling, storage, and downstream processing. Current strategies are either too expensive or insufficiently scalable for widespread adoption in SMEs. Despite extensive research on membrane- and fermentation-based valorisation, mechanical or low-energy separation approaches remain underexplored.

Innovations such as reverse centrifugal expulsion and integrated membrane systems show promise in reducing total solids, lowering treatment costs, and facilitating resource recovery. Addressing this gap could simultaneously mitigate environmental hazards and support the development of a sustainable circular bioeconomy in the dairy sector. The reverse centrifugal mechanism, originally developed for solid-liquid separation in other food applications, offers an energy-efficient, scalable, and hygienic alternative. By employing centrifugal forces in a reverse configuration, this technique can enhance whey expulsion and lower total solids without relying on high pressure or chemical treatment. However, systematic studies investigating its performance, optimization, and impact on whey composition and *paneer* yield are limited.

Therefore, the present research addresses this gap by testing a semi-automatic reverse centrifugal expulsion prototype for *paneer* manufacturing, with specific emphasis on its ability to reduce whey solids, improve product yield, and enhance hygienic handling. The outcomes are expected to provide SMEs with a cost-effective, environmentally sustainable, and technologically feasible solution for whey management and utilization. The aim of this study was to evaluate the performance of reverse centrifugal expulsion in reducing total solids in whey during production of *paneer* using reverse centrifugal technique.

Material and methods

Experimental Procedure

The experimental system (currently being considered for patent filing) was a semi-automatic batch-type prototype, integrating a processing vessel, insulated jacket, agitator, acid dosing unit, reverse centrifugal pressing chamber, and control panel. Ten and half litre of distilled water was poured into heating jacket. Buffalo milk procured from Experimental dairy plant, ICAR-NDRI, Karnal, Haryana (India) was standardised to Fat:SNF::1:1.65 using buffalo skimmed milk and filtered. Then 10.25 kg of standardised milk (% Fat 5.60 ± 0.08 and % SNF 9.23 ± 0.14) was poured into the prototype's processing vessel fitted with mechanised stirrer and heated to 82 °C and held for 5 minutes. Thereafter milk was cooled to set coagulation temperature (70, 75 and 80 °C) by replacing a part of hot water in the jacket of isothermal centrifugal filtration assembly with tap water. Then 1 % (w/v) citric acid solution which was already heated to set coagulation temperature (70, 75 and 80 °C) was supplied via coagulant dosing system to the milk along with continuous stirring till clear whey separation was observed. Then stirrer was removed from the system and centrifugally expanding pressing assembly lined with muslin cloth (filter medium) was inserted in its place inside the vessel. Then drain valve was open manually to allow drainage of freely separated out whey. Then centrifugal assembly was operated at fixed process parameters like speed of rotation (controlled by variable frequency drive to yield 235.3, 253.4, 271.5 and 289.6 RPM) and pressing time (3, 4, 5 minutes) keeping system running at fixed coagulation temperature. A vessel for whey collection was placed at bottom of drain pipe and drain valve was kept open. After set time rotation of machine was stopped and whey was allowed to flow out of drain pipe to the whey collection vessel. Whey collected was then measured. After whey collection data recording was completed, centrifugal assembly was removed from the vessel and a cut was made in the coagulum cake in axial direction of vessel. Coagulum was then removed from the vessel and weighed. Finally it was stored in chilled brine (20 % Sodium chloride w/v in water) in refrigerator.

In traditional centrifugation involving solid liquid separation, liquid is strained at the periphery using a suitable mesh size strainer. In reverse centrifugal mechanism liquid is collected / expelled from near the axis while solids collect on the periphery.

Physico-chemical parameters studied

Physcio chemical characteristics of whey were determined using standard methods. Solids-not-fat (SNF) content (% wb) and TS content in whey (% wb) were determined gravimetrically using

FSSAI 01.025:2022 method (FSSAI, 2022). Moisture content in whey (% wb) was determined as difference of TS from 100. Fat content in whey (% wb) was determined using Rose Gottlieb method as described in FSSAI 01.024:2022 (FSSAI, 2022). pH was measured using calibrated generic benchtop pH meter with whey samples equilibrated at 25.0 ± 0.1 °C. Viscosity (mPa.s) was determined using IKA Lo-Vi Rotational Viscometer using extremely low viscosity adapter spindle set (ELVAS) at 60 RPM on whey samples equilibrated at 20.0 ± 0.1 °C. Density (kg/m³) was determined using 25 mL pycnometer with whey samples equilibrated at 25.0 ± 0.1 °C. *Paneer* quantity obtained (kg) was weighed and yield (ratio of *paneer* to milk, % by weight) was determined for each trial. All determined parameters have been tabulated in Table 1.

Statistical analysis

A total of 20 experimental trials (Table 1) were conducted in a randomized order following response surface analysis using I-optimal design (Walsh et. al., 2024) with point exchange. Design of experiments was planned using Design expert 13.0.5.0 software (Stat-Ease, 2021). Optimal designs begin with a pseudo-random set of model points (runs) that are capable of fitting the designed for model for best average prediction precision. The initial selection can usually be improved by replacing a subset of the points with better selections. In this design, coagulation temperature was varied at three levels (70°C, 75°C, and 80°C), while the speed of rotation was regulated using a variable frequency drive to achieve speeds of 235.3, 253.4, 271.5, and 289.6 RPM. The pressing time, was kept at three levels of 3, 4, and 5 minutes. The experimental data were compiled and analyzed using Microsoft Excel (Microsoft Corporation, 2013), Design expert (Stat-Ease, 2021), and R Studio version 4.5.1 (R Core Team, 2025). Analysis of variance (ANOVA) was performed (Table 2) to determine the effect of each factor. Regression analysis (Table 3, Figure 1) was performed using modified linear model excluding all non-significant terms. Correlation analysis between all possible pair combination of factors and responses was also performed using R studio version 4.5.1 (Figure 2).

Experimental Validation of optimized solution

Response surface plots were generated (Figure 1) and responses were numerically optimized using Design expert 13.0.5.0 software which provides optimum conditions under criteria listed in Table 4 within range of experimental data. The experiments were conducted in triplicates at optimum conditions. To test the significance difference between experimental and predicted value

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

Coagulation Temperature (°C)	RPM	Pressing Time (min)	Whey Moisture (%)	Whey TS (%)	Whey Fat (%)	Whey SNF (%)	Whey pH	Whey Viscosity (mPa.s)	Whey Density (kg/m³)	*Paneer* (kg)	Yield (%)
70	235.3	3	95.11	4.89	0.11	4.78	6.0	1.70	1025	2.28	22.24
80	253.4	3	94.50	5.50	0.13	5.37	5.3	1.78	1028	2.04	19.81
75	271.5	3	94.96	5.04	0.12	4.92	5.8	1.72	1026	2.07	20.10
75	271.5	3	94.85	5.15	0.12	5.03	5.7	1.73	1026	2.12	20.60
75	271.5	3	94.93	5.07	0.12	4.95	5.8	1.72	1026	2.07	20.16
70	289.6	3	95.11	4.89	0.11	4.78	6.0	1.70	1025	2.22	21.68
80	289.6	3	94.50	5.50	0.13	5.37	5.3	1.78	1028	2.00	19.46
75	235.3	4	94.76	5.24	0.12	5.12	5.6	1.75	1027	2.19	21.32
80	235.3	4	94.62	5.38	0.13	5.25	5.4	1.77	1028	2.01	19.55
70	253.4	4	95.11	4.89	0.11	4.78	6.0	1.70	1025	2.27	22.06
70	253.4	4	95.29	4.71	0.11	4.60	6.2	1.67	1024	2.17	21.11
80	271.5	4	94.62	5.38	0.13	5.25	5.4	1.77	1028	1.95	19.10
70	289.6	4	95.19	4.81	0.11	4.70	6.1	1.69	1025	2.17	21.21
75	289.6	4	94.85	5.15	0.12	5.03	5.7	1.73	1026	2.09	20.35
75	289.6	4	94.76	5.24	0.12	5.12	5.6	1.75	1027	2.11	20.65
70	235.3	5	95.11	4.89	0.11	4.78	6.0	1.70	1025	2.28	22.16
75	235.3	5	94.85	5.15	0.12	5.03	5.7	1.73	1026	2.14	20.88
80	271.5	5	94.62	5.38	0.13	5.25	5.4	1.77	1028	1.97	19.13
80	271.5	5	94.50	5.50	0.13	5.37	5.3	1.78	1028	2.00	19.51
70	289.6	5	95.29	4.71	0.11	4.60	6.2	1.67	1024	2.12	20.68
Minimum			94.50	4.71	0.11	4.60	5.30	1.67	1024	1.95	19.10
Maximum			95.29	5.50	0.13	5.37	6.20	1.78	1028	2.28	22.24
Mean			94.88	5.12	0.12	5.00	5.72	1.73	1026	2.11	20.59
SD			0.264	0.264	0.008	0.256	0.308	0.037	1.350	0.102	0.995

at optimum parameters, student's t-test ($p<0.05$) was used. The Equation (1) was used for computing R_d values (Lamauro et al.1985):

$$R_d = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{Q_{i_{exp}} - Q_{i_{pre}}}{Q_{i_{exp}}}\right| \tag{1}$$

Where, R_d is relative deviation percent, $Q_{i_{exp}}$ is experimental value of response and $Q_{i_{pre}}$ is predicted value of response.

Results and Discussion

Effect of factors on various responses was studied and analysed using various statistical techniques like ANOVA (Table 2), regression analysis (Table 3), response surface plots (Figure 1), and correlation analysis (Figure 2) as described below.

Effect of process parameters on physico-chemical characteristics of whey

Moisture content in whey was found to be varying from 94.50 to 95.29 % (94.88 ± 0.264 %), where as TS, Fat and SNF content, in whey varied from 4.71 to 5.50 % (5.12 ± 0.264 %), 0.11 to 0.13 % (0.12 ± 0.008 %), and 4.60 to 5.37 % (5.00 ± 0.256 %) respectively during the experimental trials. pH, viscosity and density of whey were found to be varying from 5.30 to 6.20 (5.72 ± 0.308), 1.67 to 1.78 mPa.s (1.73 ± 0.037 mPa.s) and 1024 to 1028 kg/m^3 (1026 ± 1.350 kg/m^3) respectively (Table 1).

Analysis of Variance (Table 2) showed that all determined physico-chemical characteristics were significantly ($p<0.01$) affected by only coagulation temperature and not affected by speed of rotation and pressing time; except fat content, which was almost constant throughout the trials. 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 affected physico-chemical parameters and tabulated in table 3. It was observed that moisture content and pH of whey reduced significantly with reduction in coagulation temperature while

TS, SNF and density of whey significantly increased with increase in coagulation temperature. As reported by Ong et. al. 2011, at lower coagulation temperature, the cheese curd gel showed fine, interconnected protein strands forming a uniform network, whereas at higher temperature, the microstructure was irregular, coarse, and less continuous. This might mean that increasing coagulation temperature may increase TS loss from coagulum to whey. Sahu and Das (2010) also reported similar trend with respect to decrease in area under temperature time graph increases TS recovery in product. Whey viscosity and density showed a increasing trend with increase in coagulation temperature (Table 3, Figure 1 a-f). This may be due to increasing TS of whey with increase in coagulation temperature. It was also observed that none of the whey parameters were affected by either speed of rotation or pressing time. Coefficient of determination (R^2) of various parameters studied ranged from 0.9107 to 0.9389 indicating that fitted model was able to explain more than 91 % 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 for all parameters 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 23 indicating an adequate signal. Hence it could be inferred that the fitted models can be used to navigate the design space (Table 3).

Effect of process parameters on *paneer* quantity and yield

Paneer (% Fat 26.68 ± 1.01and % SNF 22.82 ± 0.64) quantity was found to be varying from 1.95 to 2.28 kg (2.11 ± 0.102 kg) while Yield varied from 19.10 to 22.24 % (20.59 ± 0.995 %) during the experimental trials (Table 1).

Analysis of Variance (Table 2) showed that both *paneer* quantity and yield were significantly ($p<0.01$) affected by coagulation temperature and speed of rotation but not affected by pressing time. 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 both *paneer* quantity and yield and tabulated in table 3. It was observed that *paneer* quantity and yield reduced significantly with reduction in coagulation temperature and speed of rotation both linearly (Table 3, Figure 1 g-h). This effect can be attributed to increase of TS loss with coagulation temperature as discussed in previous section in agreement with Ong et. al. 2011. Sahu and Das (2010) also reported similar trend with respect to decrease in area under temperature time graph increases TS recovery in product. It was also observed that none of the *paneer* quantity and yield was affected by pressing time. Coefficient of determination (R^2) of *paneer* quantity and yield was 0.8886 and 0.8879 respectively indicating that fitted model was able to explain more than 88 % 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 for both parameters 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 21 indicating an adequate signal. Hence it could

Table 2: Analysis of variance for various (a) whey and (b) product parameters on modified linear model for response surface analysis using I-optimal design with point exchange

(a) Whey Parameters	Source	Model	Coagulation Temperature	Residual	Lack of Fit	Pure Error	Cor Total
	df	1	1	18	13	5	19
Moisture (%)	SS	1.22	1.22	0.1009	0.0669	0.0339	1.32
	MSS	1.22	1.22	0.0056	0.0051	0.0068	
	F	217.61**	217.61**		0.759^{NS}		
	p	< 0.0001	< 0.0001		0.6838		
TS (%)	SS	1.22	1.22	0.1009	0.0669	0.0339	1.32
	MSS	1.22	1.22	0.0056	0.0051	0.0068	
	F	217.61**	217.61**		0.759^{NS}		
	p	< 0.0001	< 0.0001		0.6838		
SNF (%)	SS	1.14	1.14	0.1009	0.0669	0.0339	1.24
	MSS	1.14	1.14	0.0056	0.0051	0.0068	
	F	203.65**	203.65**		0.759^{NS}		
	p	< 0.0001	< 0.0001		0.6838		
pH	SS	1.69	1.69	0.1098	0.0731	0.0367	1.8
	MSS	1.69	1.69	0.0061	0.0056	0.0073	
	F	276.65**	276.65**		0.7672^{NS}		
	p	< 0.0001	< 0.0001		0.6786		
Viscosity (mPa.s)	SS	0.0234	0.0234	0.0023	0.0015	0.0008	0.0257
	MSS	0.0234	0.0234	0.0001	0.0001	0.0002	
	F	183.67**	183.67**		0.7659^{NS}		
	p	< 0.0001	< 0.0001		0.6794		
Density (kg/m³)	SS	31.57	31.57	2.82	1.87	0.9473	34.39
	MSS	31.57	31.57	0.1565	0.1438	0.1895	
	F	201.73**	201.73**		0.759^{NS}		
	p	< 0.0001	< 0.0001		0.6838		

(b) Product Parameters	Source	Model	Coagulation Temperature	RPM	Residual	Lack of Fit	Pure Error	Cor Total
	df	2	1	1	17	12	5	19
Paneer (kg)	SS	0.1758	0.1532	0.0187	0.022	0.0147	0.0073	0.1979
	MSS	0.0879	0.1532	0.0187	0.0013	0.0012	0.0015	
	F	67.82**	118.17**	14.42**		0.8382^{NS}		
	p	< 0.0001	< 0.0001	0.0014		0.6311		
Yield (%)	SS	16.72	14.79	1.57	2.11	1.39	0.7234	18.83
	MSS	8.36	14.79	1.57	0.1241	0.1156	0.1447	
	F	67.33**	119.15**	12.62**		0.7989^{NS}		
	p	< 0.0001	< 0.0001	0.0024		0.6547		

SS: sum of squares; df: degree of freedom; MSS: mean sum of squares; F: ratio of variances; p: probability; NS: Not Significant; *: Significant at 5 % level ($p \leq 0.05$); **: Significant at 1% level ($p \leq 0.01$)

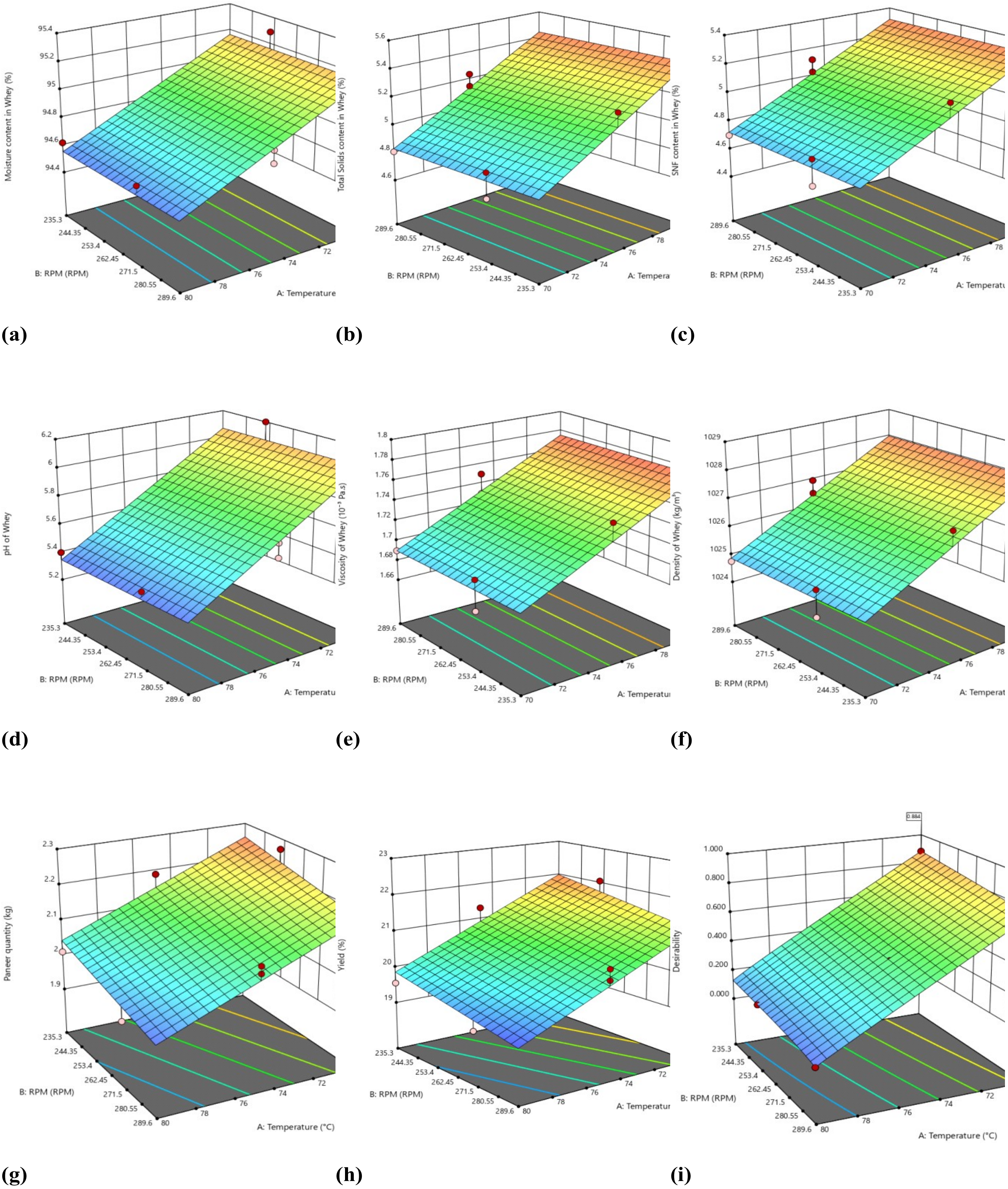

Fig. 1 Response surface and contour plots of (a) Whey Moisture (%), (b) Whey TS (%), (c) Whey Fat (%), (c) Whey SNF (%), (d) Whey pH, (e) Whey Viscosity (mPa.s), (f) Whey Density (kg/m³), (g) *Paneer* (kg), (h) Yield (%) and (i) numerical optimisation desirability plot as influenced by level of coagulation temperature and RPM during pressing step by reverse centrifugal expulsion technique for response surface analysis of fitted modified linear model using I-optimal design with point exchange.

be inferred that the fitted models can be used to navigate the design space (Table 3).

Correlation analysis among the studied variables

The correlation analysis revealed clear interrelationships among process parameters, whey characteristics, and *paneer* yield. *Paneer* yield exhibited strong negative correlations with whey density (-0.75), viscosity (-0.74), pH (-0.77), SNF (-0.75), fat (-0.89), and total solids (-0.76), indicating that higher nutrient losses into whey directly reduced *paneer* recovery. Whey constituents such as fat, SNF, TS, and pH were strongly and positively interrelated ($r > 0.95$), suggesting that loss of one component was accompanied by simultaneous loss of others.

Among process variables, coagulation temperature emerged as the most critical factor, showing significant positive correlations with whey fat (0.96), SNF (0.97), TS (0.96), and pH (0.95). This demonstrates that elevated coagulation temperatures promoted higher transfer of solids into whey, thereby reducing yield. Speed of rotation showed moderate negative correlations with whey density (-0.34) and yield (-0.32), reflecting a limited but favourable role in whey expulsion. In contrast, pressing time had negligible correlations with yield and whey composition (<0.05), highlighting its negligible influence compared to coagulation temperature and speed of rotation.

The heat map (Figure 2) shows that *paneer* yield depends mainly on coagulation temperature and whey composition. High

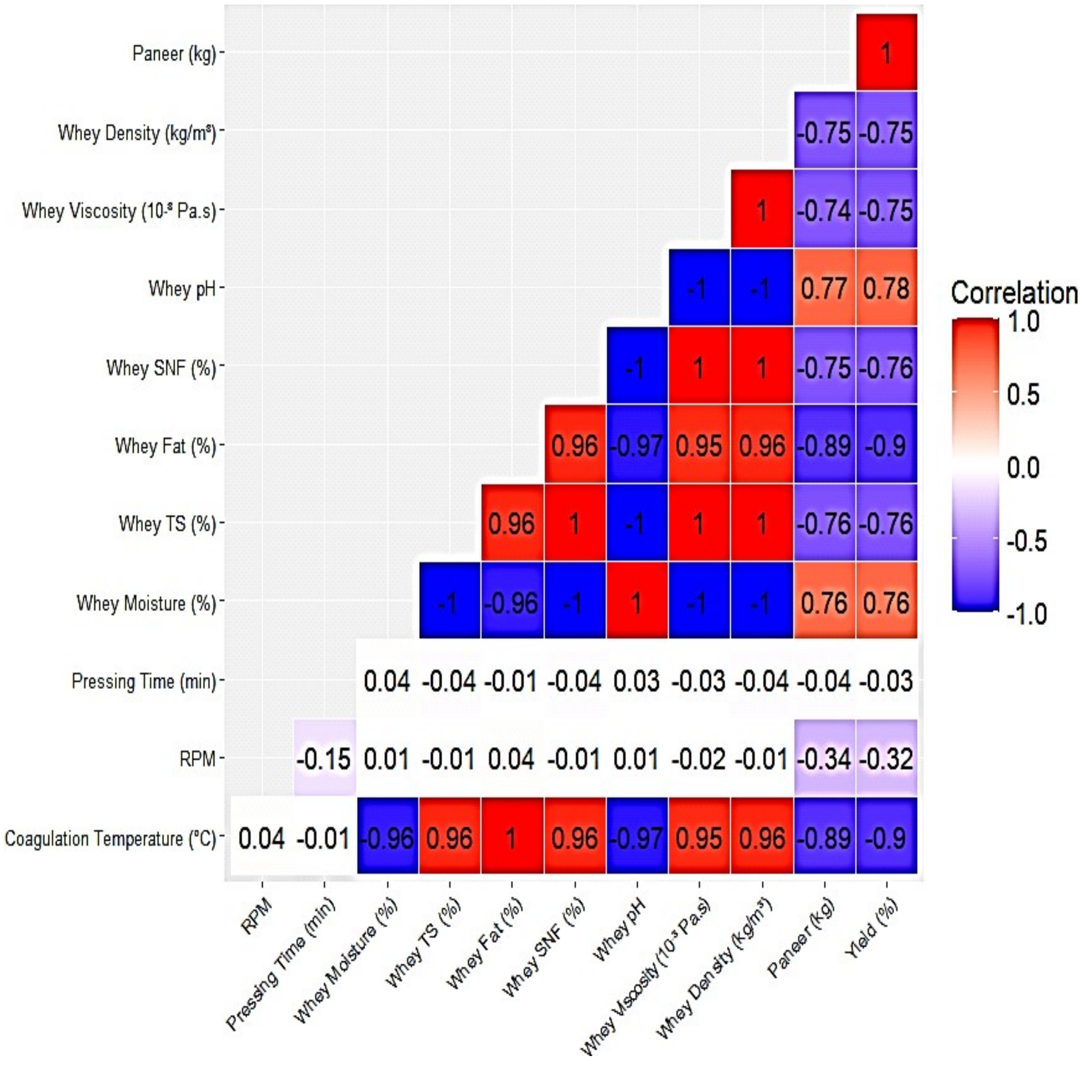

Fig. 2 Correlation heat map of various parameters under study for *paneer* making using reverse centrifugal expulsion technique for response surface analysis of fitted modified linear model using I-optimal design with point exchange

coagulation temperatures cause greater loss of solids and fat into whey, reducing yield. Optimizing temperature (and to a lesser extent RPM) is essential to minimize whey losses and improve *paneer* yield and quality. Overall, the findings confirm that optimization of coagulation temperature, along with appropriate RPM adjustment, is essential to minimize whey losses and improve both the yield and quality of *paneer* (Figure 2).

Numerical optimisation of process parameters

Table 4 represents the constraints, criteria for optimization, solution along with predicted and actual values of responses. The criteria used for numerical optimisation were aimed at minimising TS loss in whey while maximising *paneer* yield. Using constraint criteria, the optimum process conditions were obtained as coagulation temperature of 70 °C, speed of rotation of 235.3 RPM and pressing time of 3 min with a desirability of 0.884 (Figure 1(i)). The experimental data was compared with predicted data by conducting statistical analysis (student's t-test) and it was observed that the experimental values were not significantly different from the predicted values with respect to all responses at 5% level of significance. The % R_d (calculated using Equation(1)) in order to compare the precision of fit of the model and it was less than 10, for both responses suggesting that the experimental data were in good agreement with the predicted values. Thus, the response surface optimization model was adequate.

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

Particulars	Whey Moisture (%)	Whey TS (%)	Whey SNF (%)	Whey pH	Whey Viscosity (mPa.s)	Whey Density (kg/m^3)	*Paneer* (kg)	Yield (%)
Intercept	99.4637	0.5363	0.5663	11.1220	1.0950	1003.0154	4.1293	40.1360
Coagulation Temperature (°C)	-0.0614	0.0614	0.0594	-0.0722	0.0085	0.3123	-0.0218	-0.2139
RPM	NA	NA	NA	NA	NA	NA	-0.0015	-0.0134
Pressing Time (min)	NA	NA	NA	NA	NA	NA	NA	NA
Mean	94.88	5.12	5.00	5.72	1.73	1026.36	2.11	20.59
Std. Error	0.0749	0.0749	0.0749	0.0781	0.0113	0.3956	0.036	0.3523
C.V. %	0.0789	1.4600	1.500	1.3600	0.6523	0.0385	1.700	1.7100
R^2	0.9236	0.9236	0.9188	0.9389	0.9107	0.9181	0.8886	0.8879
Adjusted R^2	0.9194	0.9194	0.9143	0.9355	0.9058	0.9135	0.8755	0.8747
Predicted R^2	0.9055	0.9055	0.8996	0.9249	0.8912	0.8987	0.8430	0.8428
Adeq Precision	25.9258	25.9258	25.0808	29.2323	23.8183	24.9618	21.3200	21.0173

NA: Not applicable; All regression coefficients were statistically significant at 1% level ($p \leq 0.01$)

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	-	-	-
RPM	in range	235.3	289.6	3	235.3	-	-	-
Pressing Time (min)	in range	3	5	3	3	-	-	-
Whey TS (%)	Minimize	4.71	5.5	3	4.832	5.05 ± 0.181	0.986^{NS}	-2.076^{NS}
Yield (%)	Maximize	19.099	22.244	3	22.005	21.81 ± 0.377	1.627^{NS}	0.895^{NS}

Actual Response Values are presented as mean ± SD; R_d: relative deviation percent; NS: Not Significant, the predicted values and actual reported values for any response differed non-significantly ($p \leq 0.05$); t Critical two-tail (at 2 degree of freedom) = 4.30265273

Future Scope

The innovation holds strong promise for further industrial application and scale-up. Integration with automation and digital monitoring systems (temperature, RPM, pH sensors) can enhance process precision and reduce operator dependency. Scaling the prototype to handle larger milk volumes can enable adoption by medium- and large-scale dairies, while modular versions can benefit cooperative and village-level units.

Beyond *paneer* production, the system offers potential for whey valorisation through recovery of whey proteins, lactose, and bioactive compounds for functional foods, beverages, and nutraceuticals. Coupling the reverse centrifugal expulsion unit with membrane filtration or fermentation technologies could open pathways for producing whey protein concentrates, bioethanol, and prebiotics in a more cost-efficient manner.

Thus, the prototype not only addresses a technological gap in *paneer* pressing, but also contributes to building a circular bioeconomy in the dairy sector by enabling sustainable whey management, value addition, and reduced environmental burden.

Conclusion

The present study successfully demonstrated the potential of a semi-automatic reverse centrifugal expulsion prototype for *paneer* manufacturing, with emphasis on whey solids reduction, yield improvement, and hygienic processing. Among the studied parameters, coagulation temperature had the most significant ($p < 0.01$) effect on whey composition and *paneer* recovery, while pressing time contributed negligibly. Optimal operating conditions were identified as 70 °C coagulation temperature, 235.3 RPM rotation speed, and 3 minutes pressing time, yielding *paneer* with minimal nutrient loss into whey and maximum recovery efficiency.

The regression models showed strong reliability ($R^2 > 0.88$, Adeq Precision > 21), and correlation analysis highlighted the critical negative relationship between *paneer* yield and whey nutrient content. Experimental validation confirmed close alignment between predicted and observed values ($p < 0.05$), establishing robustness of the optimization framework. These features make it an energy-efficient and scalable solution for small- and medium-scale dairy enterprises (SMEs).

Overall, the reverse centrifugal expulsion technique provides a cost-effective, durable, and sustainable alternative to conventional pressing, with dual benefits of improved *paneer* quality and reduced whey disposal challenges.

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