



Exploratory Response Surface Analysis of Noni Fruit Juice Extraction Using a Hot Dry Steam System

Karyanik^{1,2,*}, Aniek Iriany³, Warkoyo⁴, Iis Siti Aisyah⁵

¹ Department of Agricultural Science, Postgraduate Program, University of Muhammadiyah Malang, Malang 65145, East Java, Indonesia

² Department of Agricultural Engineering, Faculty of Agriculture, Muhammadiyah University of Mataram, Mataram 108, West Nusa Tenggara, Indonesia

³ Department of Agricultural Science, Postgraduate Program, University of Muhammadiyah Malang, Malang 65145, East Java, Indonesia

⁴ Department of Food Technology, Faculty of Agriculture and Animal Husbandry, Postgraduate Program, University of Muhammadiyah Malang, Malang 65145, East Java, Indonesia

⁵ Department of Mechanical Engineering, Faculty of Engineering, University of Muhammadiyah Malang, Malang 65145, East Java, Indonesia

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ABSTRACT

This study investigates whether temperature, pressure, and extraction time adequately explain the recovery of noni (*Morinda citrifolia* L.) juice using a Hot Dry Steam (HDS) system. Twenty observations generated from a central composite design (CCD) were analyzed using linear and full quadratic regression models. The response variable was treated as recorded mass because the source dataset reports values in kilograms (kg), although confirmation of the measurement unit is required. The observed responses ranged from 5.20 to 9.10 kg, with a mean of 7.1225 kg. The linear model was not statistically significant ($F = 0.2757$, $p = 0.8420$; $R^2 = 0.0492$; adjusted $R^2 = -0.1291$), and none of the individual factor coefficients were significant. The addition of three interaction and three quadratic terms did not significantly improve model fit ($p = 0.6157$). Similarly, the full quadratic model was not statistically significant ($p = 0.7786$; adjusted $R^2 = -0.2398$). Within the factorial design space, the linear model predicted a maximum response of 7.6049 kg at 80 °C, 2.0 bar, and 30 min, whereas the experimentally observed response under these conditions was 6.10 kg. This discrepancy, together with the lack of statistical significance and the boundary location of the predicted maximum, indicates that the prediction cannot be considered a validated optimum. Overall, the dataset supports exploratory assessment of the HDS process but does not provide sufficient evidence to establish optimal operating conditions or a comparative advantage of HDS over alternative extraction methods. Verification of operating and measurement protocols, improved control of feed variability, appropriate experimental replication, and independent validation are required before specific process conditions can be recommended.

1. Introduction

Noni (*Morinda citrifolia* L.) is processed into juice and extracts whose value depends on both product recovery and chemical quality. Wang *et al.* [1] evaluated these outcomes separately during

* Corresponding author.

E-mail address: karyanik@webmail.umm.ac.id

ultrasound- and enzyme-assisted juice extraction, highlighting the importance of distinguishing product yield from the retention of phytochemical constituents. The present study focuses specifically on juice recovery using a Hot Dry Steam (HDS) system. The medicinal efficacy and potential health benefits of noni are beyond the scope of this study.

Published methods for noni processing include pressing following pretreatment, fermentation, ultrasound-assisted extraction, and solvent-based extraction for the isolation of selected compounds. The performance of these methods depends on several factors, including feed preparation, extraction medium, energy input, process conditions, and the response variable being evaluated. In particular, steam blanching followed by mechanical pressing differs fundamentally from extraction conducted under independently controlled temperature, pressure, and processing time. Findings from these alternative processing methods therefore provide useful context but cannot be used to establish the efficiency of the HDS configuration investigated in the present study.

The central research question is whether variations in temperature, pressure, and extraction time account for sufficient variation in recovered juice volume to support a meaningful operating recommendation. A central composite design (CCD) enables the estimation of both linear and quadratic response models; however, the use of an experimental design alone is insufficient to establish optimal operating conditions. Model adequacy, parameter uncertainty, predictive performance, and independent experimental confirmation must also be considered before an optimum can be reliably established [2, 3].

Accordingly, this study analyzes 20 experimental observations obtained using the HDS system, compares linear and full quadratic response models, and evaluates the strength of the statistical evidence supporting process optimization. The principal contribution of the study is an exploratory assessment of the investigated HDS configuration based on the available experimental data. The original observations are retained, while the analysis identifies the measurement, reporting, and operating information required to support reproducible follow-up experiments and more robust optimization. No claim is made regarding the technological novelty or superiority of the HDS system relative to other noni-processing methods.

1.1 Literature review

1.1.1 Noni Extraction Methods and Response Definitions

Thirukkumar *et al.* [4] compared steam blanching, freezing and thawing, and fermentation as pretreatment methods for noni juice recovery, with the first two treatments followed by mechanical pressing. Their evaluation of phenolic content and antioxidant activity highlights the importance of distinguishing juice recovery from product quality. However, different blanching temperatures are reported in the abstract and methods sections, creating uncertainty regarding the precise experimental conditions. Consequently, the study provides useful context for comparing noni-processing approaches but does not offer a sufficiently reliable temperature benchmark for evaluating the HDS process.

Wang *et al.* [1] compared ultrasound treatment, enzymatic treatment, and their combination, reporting a maximum juice yield of 67.95% following enzymatic pretreatment and subsequent ultrasound treatment at 600 W for 10 min. Although these findings are directly relevant to noni juice processing, the reported percentage yield cannot be directly compared with an absolute recovered mass unless the initial mass of the fruit is known. Moreover, ultrasound power and enzymatic action represent fundamentally different process mechanisms from the operating variables considered in

the HDS system. Therefore, the optimized conditions reported by Wang *et al.* [1] cannot be directly transferred to the HDS configuration investigated in the present study.

Other extraction studies have focused primarily on the recovery of specific bioactive compounds rather than on bulk juice recovery. Microwave-assisted extraction of anthraquinones from noni roots was discussed in the subsequent errata and review by Suktham *et al.* [5], whereas Shotipruk *et al.* [6] investigated pressurized hot-water extraction of anthraquinones from noni roots. Differences in plant tissue, extraction medium, process conditions, and analytical endpoints preclude a meaningful quantitative comparison of these methods with fruit juice recovery using HDS. Furthermore, these studies do not provide sufficient evidence to establish either the magnitude or direction of the pressure effect within the HDS system.

For noni fruit, Jamaludin *et al.* [7] reported compound-specific responses to subcritical water temperature. The recovery of scopoletin and alizarin increased as the temperature increased from 100 to 140 °C, whereas rutin recovery reached a maximum at 120 °C before subsequently declining. Gong *et al.* [8] employed quadratic models to evaluate the effects of temperature, extraction time, and liquid-to-solid ratio during ethanol extraction. Collectively, these findings demonstrate that responses to temperature and processing time depend strongly on the target compound, extraction medium, and process conditions. They therefore cannot be used to infer that increasing temperature or extraction time would necessarily increase or decrease bulk juice recovery in an HDS system.

Processing and storage history further complicate comparisons based solely on product recovery. Yang *et al.* [9] evaluated radical-scavenging activity and total phenolic content in noni juice and powder and reported reductions under several processing and storage conditions. Wang *et al.* [10] monitored changes in phenolic compounds, polysaccharides, and volatile profiles during noni juice fermentation, while Arkorful *et al.* [11] evaluated ascorbic acid and brine pretreatments prior to fermentation using measurements of bioactive compounds and antioxidant activity. Collectively, these studies emphasize the importance of evaluating chemical quality alongside product recovery. However, their pretreatment procedures, fermentation periods, and processing mechanisms differ substantially from those of HDS. Consequently, a greater recovered mass alone should not be interpreted as evidence of superior product quality or overall process performance.

1.1.2 Evidence Gap and Experimental Design

The remaining evidence gap is specific to the HDS process. Published studies on chemical-extraction kinetics, pretreatment methods, and percentage juice yields do not establish how the three recorded HDS operating variables—temperature, pressure, and extraction time—affect the recovered mass of noni juice. A meaningful comparison with alternative extraction methods would require comparable raw materials, standardized feed loading, a consistent definition of recovery, and appropriate measurements of product quality. Because the present experiment does not include a conventional-extraction control, it cannot be used to establish the comparative efficiency or superiority of the HDS process.

The central composite design (CCD) comprises factorial points, axial points, and replicated center points. The factorial points provide information for estimating the main effects and interactions among factors, while the axial points enable the estimation of quadratic terms and the assessment of response curvature. Replication at the center point provides a local estimate of pure experimental error. Collectively, these design features enable the adequacy of alternative model forms to be

evaluated rather than assuming that the existence of a fitted response surface necessarily indicates successful process optimization [2].

Reliable statistical interpretation also requires adequate characterization of the experimental process. Nominal temperature and pressure settings alone do not fully characterize the conditions experienced by the fruit unless the steam conditions, sensor locations, pressure reference, treatment duration, and timing procedures are clearly documented. Insufficient information on these parameters limits experimental reproducibility and prevents a robust mechanistic interpretation of the estimated model coefficients.

1.1.3 Response Surface Methodology

Response surface methodology (RSM) integrates statistically designed experiments with empirical modelling to characterize the relationship between a response and a set of experimental factors within a defined design space. A first-order model represents the response as a plane, whereas a full second-order model incorporates pairwise interaction and quadratic terms to account for potential curvature in the response surface. Estimation of these additional terms enables the investigation of a possible interior optimum; however, fitting a second-order model does not, by itself, guarantee adequate predictive performance or establish the existence of a meaningful optimum [3, 12]. The sequential optimization strategy originally introduced by Box and Wilson [13] similarly emphasizes the importance of iterative experimentation and experimental confirmation before an operating optimum is accepted.

In the present study, alternative model forms are evaluated using overall F-tests, adjusted R^2 values, an extra-sum-of-squares test for the six additional terms in the quadratic model, and lack-of-fit tests based on replicated center-point observations. Importantly, failure to detect statistically significant lack of fit should not be interpreted as evidence of predictive adequacy, particularly when the number of replicated observations is limited and statistical power is consequently low. Therefore, specific operating conditions are considered suitable for recommendation only when supported by adequate model fit, statistical evidence, predictive performance, and appropriate experimental validation.

2. Methodology

Physiologically ripe noni (*Morinda citrifolia* L.) fruit was processed using a system designated as Hot Dry Steam (HDS), with temperature (T), pressure (P), and extraction time (t) selected as the experimental factors. The analysis was based on the 20 experimental observations and corresponding factor settings reported in Table 1. The central composite design (CCD) consisted of eight factorial runs, six axial runs, and six replicated center-point runs at 90 °C, 1.5 bar, and 45 min. The factorial levels ranged from 80 to 100 °C for temperature, 1.0 to 2.0 bar for pressure, and 30 to 60 min for extraction time. The axial limits were 73.18–106.82 °C, 0.659–2.341 bar, and 19.77–70.23 min, corresponding to coded distances of approximately ± 1.682 .

The response column in the original dataset was labeled “Actual volume (Kg).” Because kilograms (kg) are a unit of mass rather than volume, the original numerical observations were retained without modification and are referred to in this study as recorded juice mass. No conversion to liters or milliliters was performed because neither juice-density measurements nor independent volumetric records were available. Furthermore, the initial fruit mass and the potential contribution of steam

condensate to the recovered liquid were not specified. Consequently, neither percentage juice yield nor fruit-derived liquid recovery could be reliably calculated from the available data.

The available experimental records do not provide sufficient information regarding fruit source or batch, initial feed load, sample preparation or size reduction, HDS equipment geometry, steam flow rate or dryness, direct or indirect steam contact, drainage and filtration procedures, or instrument calibration. The precise criteria defining the beginning and end of the timed treatment are also not documented. In addition, the records do not indicate whether the reported pressure values represent gauge or absolute pressure, where temperature was measured within the system, or whether temperature and pressure were measured at the same location. Accordingly, HDS is retained throughout this study as the supplied designation for the experimental equipment; however, the thermodynamic state of the steam and the extent to which temperature and pressure were independently controlled cannot be verified from the available records.

Ordinary least-squares regression was used to fit all 20 observations. The first-order linear model comprised an intercept and the three main effects of temperature, pressure, and extraction time. The full second-order model additionally incorporated three pairwise interaction terms and three quadratic terms. Model performance and comparison were evaluated using overall F-tests, the coefficient of determination (R^2), adjusted R^2 , and an extra-sum-of-squares F-test for the additional second-order terms, with statistical significance assessed at $\alpha = 0.05$. Lack of fit was evaluated relative to pure error estimated from the six replicated center-point observations. This partition assumes that the center-point runs represent independent experimental replicates with a common error variance. However, the independence of these replicates and the actual experimental run order could not be verified from the available records and therefore require confirmation from the original experimental documentation.

Model diagnostics included a normal quantile plot, a histogram of residuals, residuals plotted against fitted values, and residuals plotted against the run index reported in Table 1. The Shapiro–Wilk test was additionally used to supplement the graphical assessment of residual normality. All calculations were performed using the rounded factor settings presented in Table 1; consequently, minor numerical differences may arise if the analyses are repeated using the original unrounded design matrix. Only a single response variable was available for analysis. Therefore, no multi-response desirability optimization was performed, and no independent confirmation experiment was available to validate the model predictions or any candidate operating conditions.

3. Results and Discussion

3.1 Response range and observed variation

The recorded juice mass ranged from 5.20 to 9.10 kg, with a mean value of 7.1225 kg. The minimum response was observed in run 1 at the center-point setting, whereas the maximum response was recorded in runs 12 and 18 under different operating conditions. These observations define the range of juice recovery represented in the experimental dataset; however, the observed minimum and maximum values alone do not provide evidence of a statistically significant treatment effect or establish optimal operating conditions.

Table 1 presents all 20 experimental observations together with the corresponding fitted values and residuals obtained from the linear model using the reported factor settings. The fitted responses ranged from 6.6401 to 7.6049 kg, which is substantially narrower than the observed range of 5.20–9.10 kg. In particular, runs 12 and 18 both yielded the maximum observed response of 9.10 kg, whereas the corresponding model predictions were only 7.4708 and 7.5093 kg, respectively. The inability of the fitted values to reproduce these relatively high observed responses, together with the

compressed range of model predictions, indicates that the linear model captures only a limited proportion of the variability present in the experimental data.

Table 1

Experimental settings, recorded juice mass, linear fitted values, and residuals

Run	Temperature (°C)	Pressure (bar)	Time (min)	Mass (kg)	Fitted (kg)	Residual (kg)
1	90.00	1.500	45.00	5.20	7.1225	-1.9225
2	90.00	1.500	70.23	5.85	7.0097	-1.1597
3	80.00	2.000	30.00	6.10	7.6049	-1.5049
4	80.00	1.000	60.00	6.00	7.1001	-1.1001
5	100.00	1.000	60.00	6.85	6.6401	0.2099
6	90.00	0.659	45.00	7.20	6.8107	0.3893
7	90.00	1.500	19.77	6.90	7.2353	-0.3353
8	100.00	2.000	60.00	7.80	7.0108	0.7892
9	90.00	1.500	45.00	8.35	7.1225	1.2275
10	106.82	1.500	45.00	7.50	6.7357	0.7643
11	100.00	2.000	30.00	8.60	7.1449	1.4551
12	80.00	2.000	60.00	9.10	7.4708	1.6292
13	90.00	1.500	45.00	6.10	7.1225	-1.0225
14	90.00	1.500	45.00	7.20	7.1225	0.0775
15	90.00	1.500	45.00	7.50	7.1225	0.3775
16	80.00	1.000	30.00	8.35	7.2342	1.1158
17	100.00	1.000	30.00	5.85	6.7742	-0.9242
18	73.18	1.500	45.00	9.10	7.5093	1.5907
19	90.00	1.500	45.00	6.90	7.1225	-0.2225
20	90.00	2.341	45.00	6.00	7.4343	-1.4343

3.2 Regression Equations and Coefficient Interpretation

The experimental factors were expressed in coded form as $x_1 = (T - 90)/10$, $x_2 = (P - 1.5)/0.5$, and $x_3 = (t - 45)/15$, where T denotes temperature (°C), P denotes pressure (bar), and t denotes extraction time (min). The coded factors are dimensionless and are centered at the corresponding center-point conditions of 90 °C, 1.5 bar, and 45 min.

The refitted linear regression equation for the predicted juice mass ($\hat{y}$, kg) in terms of the coded factors is:

$$\hat{y} = 7.122500 - 0.229986x_1 + 0.185353x_2 - 0.067073x_3.$$

Application of the coding relationships yields the equivalent equation expressed in the original experimental units:

$$\hat{y} = 8.837530 - 0.0229986T + 0.370706P - 0.00447153t.$$

The coefficients of the coded and original-unit equations should be interpreted according to their respective factor scales. In the coded equation, a one-unit change in x_1 , x_2 , or x_3 corresponds to a change of 10 °C, 0.5 bar, or 15 min, respectively. In contrast, the coefficients in the original-unit equation represent the estimated change in predicted juice mass associated with a one-unit change in temperature (1 °C), pressure (1 bar), or extraction time (1 min), while the other factors are held constant. Transformation from coded to original units therefore changes both the numerical values of the slopes and the intercept but does not alter the fitted response surface. Accordingly, both equations predict a juice mass of 7.1225 kg at the design center (90 °C, 1.5 bar, and 45 min).

For subsequent model comparisons, L denotes the linear model and Q denotes the full quadratic model. The reported coefficient estimates, standard errors, and confidence intervals are expressed on the kilogram response scale, with the predictors represented by dimensionless coded factors. Interaction and squared terms are not included in model L but are incorporated in model Q . All

coefficient estimates were calculated using the rounded experimental settings reported in Table 1; therefore, minor numerical differences may occur if the models are refitted using the original unrounded design matrix.

Table 2

Coded coefficients and uncertainty for the linear and full quadratic models

Model/term	Coded coef.	SE	t	p-value	95% CI
L: Intercept	7.122500	0.275223	25.879	<0.0001	[6.5391, 7.7059]
L: x_1	-0.229986	0.333044	-0.691	0.4997	[-0.9360, 0.4760]
L: x_2	0.185353	0.333044	0.557	0.5855	[-0.5207, 0.8914]
L: x_3	-0.067073	0.333044	-0.201	0.8429	[-0.7731, 0.6389]
Q: Intercept	6.867716	0.526026	13.056	<0.0001	[5.6957, 8.0398]
Q: x_1	-0.229986	0.348986	-0.659	0.5248	[-1.0076, 0.5476]
Q: x_2	0.185353	0.348986	0.531	0.6069	[-0.5922, 0.9629]
Q: x_3	-0.067073	0.348986	-0.192	0.8514	[-0.8447, 0.7105]
Q: x_1x_2	0.356250	0.455995	0.781	0.4527	[-0.6598, 1.3723]
Q: x_1x_3	-0.056250	0.455995	-0.123	0.9043	[-1.0723, 0.9598]
Q: x_2x_3	0.443750	0.455995	0.973	0.3534	[-0.5723, 1.4598]
Q: x_1^2	0.551467	0.339683	1.623	0.1356	[-0.2054, 1.3083]
Q: x_2^2	-0.049426	0.339683	-0.146	0.8872	[-0.8063, 0.7074]
Q: x_3^2	-0.128956	0.339683	-0.380	0.7122	[-0.8858, 0.6279]

For the linear model, the estimated coefficients for temperature, pressure, and extraction time yielded p-values of 0.4997, 0.5855, and 0.8429, respectively. None of these effects was statistically significant at the 5% significance level, and all corresponding 95% confidence intervals included zero (Table 2). Although temperature had the largest absolute coefficient on the coded scale, its magnitude alone does not indicate statistical significance or establish temperature as the dominant factor influencing juice recovery. Moreover, the signs of the estimated coefficients should be interpreted cautiously. Given the substantial statistical uncertainty surrounding these estimates, they represent sample-specific directions of association rather than confirmed positive or negative effects of the process variables on recovered juice mass.

3.3 Analysis of Variance and Model Adequacy

The linear model yielded $F(3,16) = 0.2757$, $p = 0.8420$, $R^2 = 0.0492$, and an adjusted R^2 of -0.1291 . Thus, the model explained only approximately 4.92% of the observed variation in recorded juice mass, leaving approximately 95.08% unexplained. The negative adjusted R^2 indicates that the modest reduction in residual variation achieved by including the three predictors was insufficient to compensate for the number of fitted model terms. These statistical results should not be interpreted as demonstrating the presence or absence of underlying physical effects of temperature, pressure, or extraction time. Rather, the available data provide insufficient evidence that the linear model has adequate predictive capability to support process optimization.

Six observations were obtained at the center point (runs 1, 9, 13, 14, 15, and 19), providing five degrees of freedom for estimating pure error. The corresponding pure-error sum of squares was 6.07875 kg^2 . For the linear model, the lack-of-fit sum of squares was 18.16051 kg^2 with 11 degrees of freedom, yielding $F(11,5) = 1.3580$ and $p = 0.3884$. Thus, statistically significant lack of fit was not detected at $\alpha = 0.05$. However, failure to detect lack of fit should not be interpreted as evidence that the linear model is adequate, particularly given the limited degrees of freedom available for estimating pure error. Furthermore, this test alone does not establish the presence or absence of

curvature or omitted interaction effects, and the observed variability among the replicated center-point responses cannot be regarded as negligible.

The full quadratic model fitted to the same 20 observations was:

$$\hat{y} = 6.867716 - 0.229986x_1 + 0.185353x_2 - 0.067073x_3 + 0.356250x_1x_2 - 0.056250x_1x_3 + 0.443750x_2x_3 + 0.551467x_1^2 - 0.049426x_2^2 - 0.128956x_3^2.$$

Table 3 summarizes the coefficient estimates and associated uncertainty for both models. None of the non-intercept terms in the quadratic model was statistically significant, with all corresponding p-values ≥ 0.1356 .

The full quadratic model yielded $F(9,10) = 0.5917$, $p = 0.7786$, $R^2 = 0.3475$, and an adjusted R^2 of -0.2398 . Its lack-of-fit test produced $F(5,5) = 1.7365$ and $p = 0.2797$, indicating that statistically significant lack of fit was again not detected at $\alpha = 0.05$. Relative to the linear model, inclusion of the six interaction and quadratic terms reduced the residual sum of squares by 7.60473 kg^2 . However, the corresponding extra-sum-of-squares test yielded $F(6,10) = 0.7619$ and $p = 0.6157$, providing no statistically significant evidence that the additional second-order terms improved model fit. Consequently, the increase in unadjusted R^2 from 0.0492 to 0.3475 should not be interpreted as evidence of improved predictive performance, particularly because the adjusted R^2 decreased further, from -0.1291 to -0.2398 .

Table 3

ANOVA and lack-of-fit partition for the linear and full quadratic models

Source	DF	SS (kg ²)	MS (kg ²)	F	p-value
Linear model	3	1.25312	0.41771	0.2757	0.8420
Linear residual	16	24.23926	1.51495	—	—
Linear lack of fit	11	18.16051	1.65096	1.3580	0.3884
Quadratic model	9	8.85785	0.98421	0.5917	0.7786
Quadratic residual	10	16.63453	1.66345	—	—
Quadratic lack of fit	5	10.55578	2.11116	1.7365	0.2797
Pure error (shared)	5	6.07875	1.21575	—	—
Total (shared)	19	25.49237	—	—	—

Although the CCD provides sufficient design structure to estimate a second-order response surface, neither the linear nor the full quadratic model provides adequate statistical evidence to support process optimization using the available dataset. The substantial unexplained variation may arise from several sources, including heterogeneity in the fruit material, differences in initial feed loading, variation in collection procedures, measurement error, and unrecorded operating conditions. The available observations do not permit these potential sources of variability to be separated or quantified, nor do they demonstrate that nonlinear process behavior is the primary explanation for the observed variation. Additional controlled and independently replicated experiments are therefore required before reliable process relationships or optimal HDS operating conditions can be established.

3.4 Residual diagnostics

The residuals from the linear model ranged from -1.9225 to 1.6292 kg . The normal quantile plot and histogram presented in Fig. 1 provide graphical assessments of the residual distribution, while the Shapiro–Wilk test yielded $W = 0.9423$ and $p = 0.2647$. Thus, the null hypothesis of normality was not rejected at $\alpha = 0.05$. However, with only 20 observations, the statistical power to detect departures from normality is limited, and the nonsignificant result should not be interpreted as

confirmation of normality. More importantly, the relatively broad dispersion of the residuals compared with the narrow range of fitted responses remains a prominent feature of the model diagnostics and is consistent with the model's limited explanatory ability.

The residual-versus-fitted plot provides no evidence that would overcome the weak explanatory performance indicated by the regression statistics. In addition, the sequence of observations presented in Table 1 cannot be assumed to represent the randomized experimental run order because the actual execution sequence was not documented. Consequently, the residual-by-index plot cannot be used to confirm or exclude potential temporal drift, serial dependence, batch effects, or other order-related sources of variation. All observations were retained in the analysis, as the available diagnostics provided no sufficient basis for excluding individual data points. Nevertheless, these residual diagnostics are statistical assessments of model behavior and should not be interpreted as evidence of a specific underlying physical mechanism.

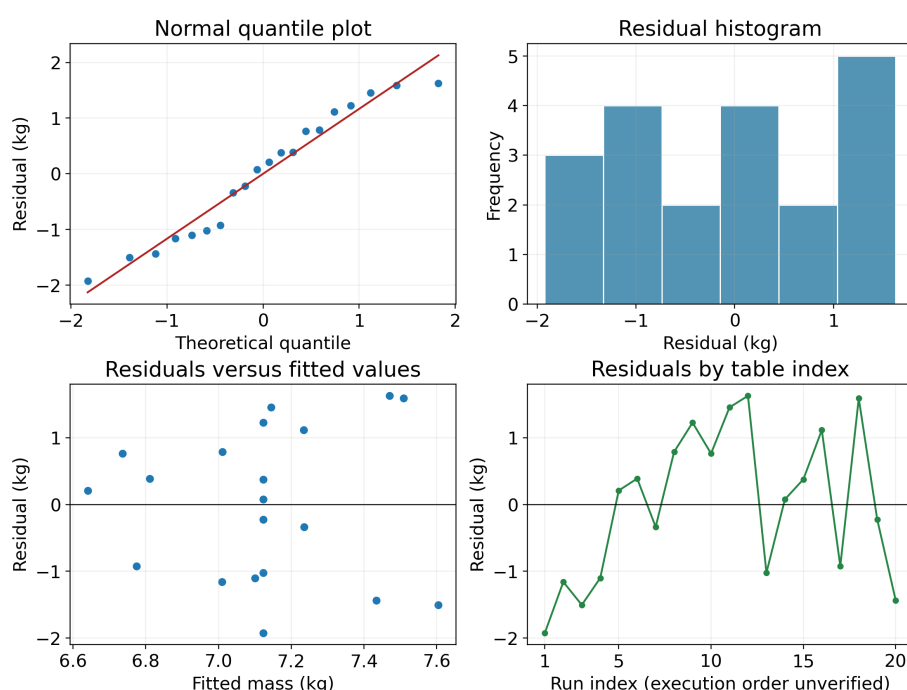


Fig. 1. Linear-model residual diagnostics reconstructed from Table 1. Residuals and fitted responses are in kg; run index follows the table order

3.5 Interpretation of the Linear Response Surfaces

The response surfaces presented in Fig. 2 are direct graphical representations of the fitted linear-model coefficients. With the third coded factor fixed at zero, each two-factor combination produces a planar response surface with straight contour lines and no interior stationary maximum. The plots are restricted to the factorial region ($-1 \leq x_i \leq +1$) and illustrate only the relationships implied by the fitted linear equation. They do not provide independent evidence that changes in temperature, pressure, or extraction time produce corresponding changes in recovered juice mass.

Similarly, the full quadratic-model assessment presented in Section 3.3 does not provide sufficient statistical evidence to establish a reliable predictive response surface. Consequently, no quadratic optimum or desirability-based operating recommendation is reported. The linear response surfaces are retained solely to provide a transparent graphical representation of the fitted model

within the investigated factorial region and should not be interpreted as evidence of model validation, predictive superiority, or confirmed process effects.

A mechanistic interpretation of the observed responses would require direct measurements of relevant physical phenomena, including heat transfer, liquid release from the fruit matrix, and the accumulation of steam condensate in the recovered product. The compound-specific thermal responses reported by Jamaludin et al. [7] further caution against assuming a universal effect of temperature on noni processing, while the findings of Wang et al. [1] demonstrate the importance of evaluating product recovery and chemical quality as distinct outcomes. Potential mechanisms such as cell-wall disruption, evaporation, case hardening, and liquid reabsorption were not measured in the present experiment. Accordingly, these mechanisms cannot be invoked as established explanations for either the magnitude or direction of the estimated model coefficients.

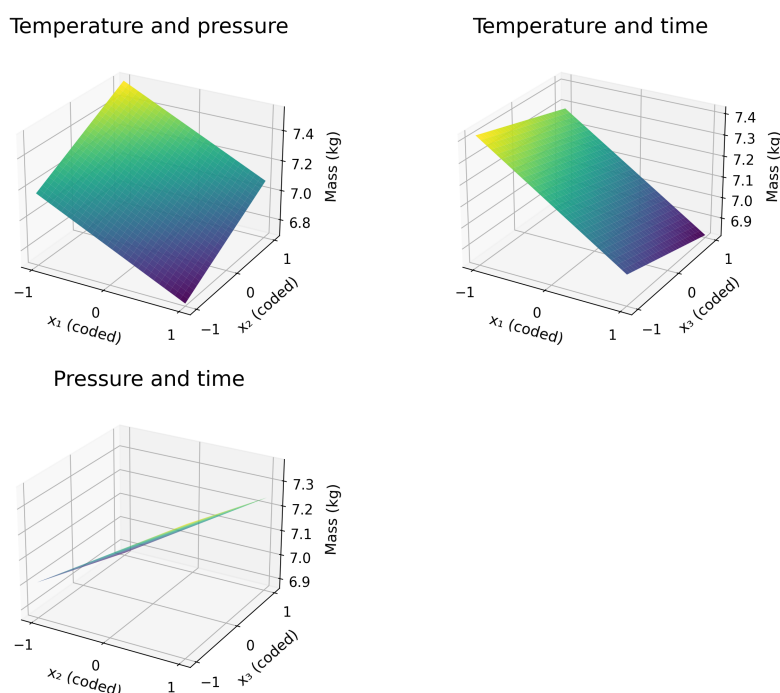


Fig. 2. Descriptive linear-model response surfaces in coded factors, with the third factor fixed at zero. The response is predicted mass in kg. These planes do not establish an optimum

3.6 Boundary Prediction and Requirements for Further Work

Within the factorial design region (80–100 °C, 1.0–2.0 bar, and 30–60 min), the linear model predicts its highest fitted response of 7.6049 kg at 80 °C, 2.0 bar, and 30 min. This value represents a mathematical boundary prediction derived from the fitted linear equation and should not be interpreted as a validated process optimum. Importantly, the same operating condition was experimentally evaluated in run 3, which yielded an observed juice mass of only 6.10 kg, corresponding to a residual of –1.5049 kg. This observed response was not the highest in the dataset and therefore provides no experimental basis for recommending this combination of operating conditions.

The axial points of the CCD extend beyond the factorial region; consequently, the boundary assessment summarized in Table 4 does not identify the maximum predicted response over the entire CCD design space. Furthermore, responses observed at individual axial points cannot be used

to infer the performance of hypothetical operating conditions that simultaneously combine multiple extreme factor levels, because such combinations were not experimentally evaluated. Extrapolation to these untested combinations would therefore not be supported by the present experimental design.

Further investigation should first establish a more complete and reproducible characterization of the HDS process. In particular, the response unit, initial feed mass, contribution of steam condensate to the collected product, and actual temperature and pressure experienced by the fruit should be verified and documented. Selected operating conditions should then be evaluated using independent replicated experiments and, where comparative performance is of interest, against an appropriately matched conventional-extraction control. Future experiments should report feed-normalized recovery together with relevant product-quality indicators, such as selected phytochemical or physicochemical properties. The number of experimental replicates should also be justified using a predefined precision or statistical power criterion. These additional measurements and confirmation experiments are necessary before reliable operating conditions or comparative process-performance claims can be established.

Table 4
Interpretation of the previously proposed boundary setting

Component	Value	Interpretation
Temperature	80.00 °C	Lower factorial level
Pressure	2.000 bar	Upper factorial level
Time	30.00 min	Lower factorial level
Linear prediction	7.6049 kg	Largest fit within factorial box only
Observed response	6.10 kg	Run 3; not the highest observation
Residual	-1.5049 kg	Observed minus predicted
Status	Unvalidated	No optimal setting established

Further engineering assessment should evaluate the energy performance of the HDS process independently of juice recovery. Prasetyo et al. [14] investigated cellulose-derived thermal-management materials for renewable-energy applications, while Prasetyo [15] examined solar-thermal catalytic biomass reforming for hydrogen production. These studies provide broader engineering context for considerations of heat supply, thermal management, and renewable-energy integration; however, neither addresses noni juice extraction nor provides evidence regarding the energy efficiency of the HDS process. Future HDS experiments should therefore quantify steam consumption, electrical energy input, condensate generation and recovery, heat losses, and specific energy consumption per unit mass of recovered product. Any proposed integration of renewable heat sources would require a separate engineering assessment addressing temperature compatibility, process controllability, product quality, energy-system boundaries, and overall process efficiency. The present dataset contains no measurements of energy consumption or associated emissions and therefore does not support claims of energy savings, improved energy efficiency, or carbon-emission reductions.

4. Conclusion

The 20-run experimental dataset provides an exploratory assessment of noni juice recovery under the recorded HDS operating conditions. However, the available evidence does not establish

optimal operating conditions or demonstrate the superiority of HDS over alternative extraction methods. Four principal conclusions can be drawn from the analysis.

1. Recorded response and study scope

The recorded response ranged from 5.20 to 9.10 kg, consistent with the unit specified in the source data table. Because kilograms represent mass rather than volume, the response was treated as recovered juice mass rather than juice volume or percentage yield. Verification of the original measurement unit and recovery protocol remains necessary. In addition, the absence of a conventional or alternative extraction comparator prevents conclusions regarding the relative extraction efficiency or performance of the HDS process.

2. Uncertainty in factor effects

None of the estimated linear effects of temperature, pressure, or extraction time was statistically significant at $\alpha = 0.05$. Although temperature had the largest absolute coefficient on the coded scale, its negative estimate does not establish that increasing temperature adversely affects juice recovery. Similarly, the positive coefficient estimated for pressure and the negative coefficient estimated for extraction time remain statistically uncertain. The directions of these coefficients should therefore be regarded as sample-specific estimates rather than confirmed process effects.

3. Model adequacy and predictive limitations

The linear model explained only 4.92% of the observed variation in recorded juice mass ($p = 0.8420$), leaving approximately 95.08% of the variation unexplained. Inclusion of all pairwise interaction and quadratic terms increased the unadjusted R^2 to 34.75%; however, the full quadratic model remained statistically nonsignificant ($p = 0.7786$) and produced an adjusted R^2 of -23.98%. Furthermore, the additional second-order terms did not significantly improve model fit relative to the linear model ($p = 0.6157$). Thus, the apparent increase in unadjusted R^2 does not provide sufficient evidence of improved predictive performance.

Section 3.2 presents the fitted equations in both coded and original factor units, with the coefficients interpreted according to their respective scales. These equations provide descriptive representations of the available dataset but should not be used to infer underlying physical mechanisms, predict performance beyond the investigated design space, or prescribe operating conditions without additional experimental validation.

4. Implications for further experimentation

At 80 °C, 2.0 bar, and 30 min, the experimentally observed response was 6.10 kg, compared with the linear model prediction of 7.6049 kg. This operating condition therefore represents neither the highest experimentally observed response nor a validated optimum. Before specific HDS operating conditions can be recommended, future studies should verify the response definition and measurement protocol, document the initial feed mass and potential contribution of steam condensate, improve control of raw-material variability, and conduct appropriately replicated confirmation experiments. Where comparative efficiency is to be assessed, a matched conventional-extraction control should also be included. Future experiments should additionally evaluate feed-normalized recovery, relevant product-quality attributes, and energy consumption. Such evidence is

required before reliable conclusions can be drawn regarding process optimization, product quality, comparative extraction performance, or the energy efficiency of the HDS system.

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