Cogent Food & Agriculture

ISSN: 2331-1932 (Online) Journal homepage: www.tandfonline.com/journals/oafa20

Response surface optimization of irrigation interval, urea rate, and guar cultivar for maximizing seed yield, biomass, galactomannan yield, and seed oil content

Mohsen Zafaranieh & Hossein Taghipoor

To cite this article: Mohsen Zafaranieh & Hossein Taghipoor (2026) Response surface optimization of irrigation interval, urea rate, and guar cultivar for maximizing seed yield, biomass, galactomannan yield, and seed oil content, Cogent Food & Agriculture, 12:1, 2672142, DOI: 10.1080/23311932.2026.2672142

To link to this article: https://doi.org/10.1080/23311932.2026.2672142

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

Published online: 20 May 2026.

Submit your article to this journal

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=oafa20

COGENT FOOD & AGRICULTURE
2026, VOL. 12, NO. 1, 2672142
https://doi.org/10.1080/23311932.2026.2672142

FOOD SCIENCE & TECHNOLOGY | RESEARCH ARTICLE

OPEN ACCESS Check for updates

Response surface optimization of irrigation interval, urea rate, and guar cultivar for maximizing seed yield, biomass, galactomannan yield, and seed oil content

Mohsen Zafaranieh[a] and Hossein Taghipoor[b]

[a]Department of Agriculture, Technical and Engineering, Velayat University, Iranshahr, Iran; [b]Faculty of Mechanical Engineering, Velayat University, Iranshahr, Iran

ABSTRACT

Water scarcity poses a major challenge to guar (*Cyamopsis tetragonoloba* L.) production in arid regions. This study objectively aimed to optimize the interactive effects of irrigation interval (6, 9, 12 days), urea rate (50, 100, 150 kg ha^{-1}), and cultivar (Brooks, Kinman, Esser) to maximize seed yield, biomass, galactomannan yield, and seed oil content using Response Surface Methodology (RSM) with Box-Behnken Design (BBD). The field experiment was conducted at Vali-e-Asr University research farm (30°23′54″N, 55°59′31″E, 1460 m) during 2023–2024 using split-factorial RCBD with three replications. Seventeen treatment combinations ensured robust model fitting ($R^2 \geq 0.98$, RMSE < 5%). Optimum conditions identified were: Kinman cultivar with 9-day irrigation + 100 kg ha^{-1} urea achieving maximum seed yield (4.19 t ha^{-1}, 34% > non-optimized baseline, 25% > prior guar studies) and biomass (8.52 t ha^{-1}, 28% improvement); Esser with 6-day irrigation + 50 kg ha^{-1} urea maximizing galactomannan (1.02 t ha^{-1}); Kinman optimizing seed oil (0.23%). Multiple-response optimum (desirability = 0.94) confirmed 9-day irrigation + 100 kg ha^{-1} urea + Kinman.Validation (n = 3) verified predictions (<3% error, $p > 0.05$), demonstrating 25–35% resource efficiency gains over conventional practices for sustainable guar production.

ARTICLE HISTORY
Received 23 September 2025
Revised 25 February 2026
Accepted 6 May 2026

KEYWORDS
Response Surface methodology; Urea fertilization; guar cultivars; seed yield; biochemical traits

SUBJECTS
Agriculture & Environmental Sciences; Plant & Animal Ecology; Botany

1. Introduction

Guar (*Cyamopsis tetragonoloba*), also known as cluster bean, is an annual leguminous crop predominantly grown in semi-arid and subtropical regions, especially in India and Pakistan. The plant reaches 2–3 meters in height, featuring a single main stem with occasional basal or stem branching. Its morphology includes elongated, oval leaves and white to bluish flowers clustered in the leaf axils (Shakir et al., 2020). Guar is rich in dietary fiber, protein, and essential vitamins and minerals, such as vitamin C, vitamin A, iron, and calcium. The high soluble fiber content of guar gum supports digestive health by improving bowel regularity, reducing constipation, and acting as a prebiotic to promote beneficial gut bacteria. Guar gum also helps regulate blood sugar levels, making it beneficial for individuals with diabetes, and may lower LDL cholesterol, supporting heart health. Additionally, guar gum increases satiety, which can aid in weight management and appetite control (Shakir et al., 2020).

Widely recognized for its drought tolerance, guar thrives on sandy and marginal soils characteristic of semi-arid climates. It produces flat, slender pods containing 5–12 seeds and forms a symbiotic association with N-fixing Rhizobium bacteria, contributing 20–100 kg N ha^{-1} to soil fertility—lower than soybeans (50–300 kg N ha^{-1}) but valuable for low-input systems (Elsheikh & Ibrahim, 1999; Thombare et al., 2016). Additionally, young pods are consumed as vegetables, and the plant serves as a source of green fodder and livestock feed (Gautam et al., 2024). Guar's adaptation to drought involves efficient water utilization, growth regulation during moisture scarcity, genetic variability in drought response, deep

CONTACT Mohsen Zafaranieh Mohsen.Zafaranieh245@gmail.com Department of Agriculture, Technical and Engineering, Velayat University, Iranshahr, Iran.

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

rooting, and heat tolerance, making it well-suited for arid and semi-arid environments (Thombare et al., 2016). Despite this resilience, drought stress significantly diminishes yield components such as grain and biomass yields and the harvest index, with notable reductions in plant height, root and pod lengths, and particularly pod number per plant, the most drought-sensitive trait (Ghorbani et al., 2019). While guar tolerates moderate water stress with minimal yield compromise, severe drought causes substantial reductions; a 50% water deficit typically decreases yields by ~26% (Garcia et al., 2023; Ghorbani et al., 2019; Vishnyakova et al., 2023). Bio-fertilizers like Mycorrhiza and Rhizobium have limited impact in offsetting drought-induced yield loss, although Rhizobium inoculation under moderate drought can enhance seed protein content. Increasing drought severity correlates with heightened protein concentration in seeds, attributed to stress-induced protein accumulation and altered gene expression related to protein synthesis (Amiri et al., 2023; Nejad et al., 2023). Fertilizer efficiency under drought stress is often limited due to impaired nutrient uptake and transport (Begna, 2020).

Irrigation during flowering and pod formation (approximately 60–70 days post-sowing) is crucial for maximizing yield. Adequate moisture at these growth stages supports flower development and pod set, while water deficits result in flower abscission and poor pod development (Meftahizade et al., 2017). Despite its drought tolerance, guar achieves optimal yield under well-timed, moderate irrigation. Excessive irrigation, conversely, promotes excessive vegetative growth and delays seed maturation, negatively affecting yield. Yield reductions intensify with increasing water stress; a 50% irrigation cut reduces yields by roughly 26%, with severe deficits halving productivity compared to fully irrigated crops (Vishnyakova et al., 2023).

The interaction between Urea management and water stress plays a crucial role in crop performance, especially under limited water conditions. Proper Urea application can mitigate the negative effects of drought by supporting metabolic activities and enhancing plant resilience, while excessive Urea may exacerbate water stress and reduce resource use efficiency (Zhai et al., 2025). Optimal water–Urea coupling not only improves root development and nutrient uptake but also increases stress tolerance and yield potential. Moreover, selecting more drought-tolerant cultivars is essential for maximizing productivity, as genetic traits can significantly influence a plant's ability to maintain growth and yield under water-limited environments. Integrating these strategies—precision Urea management and the use of drought-adapted varieties provides a robust approach for sustaining crop production in arid and semi-arid regions (Bradley, 2007).

Guar seeds contain 25–30% protein, 2–3% oil, and 30–40% galactomannan gum, along with significant levels of vitamin C (15–20 mg/100g), vitamin A, iron (5–7 mg/100g), and calcium (120–150 mg/100g). Guar gum's soluble fiber content supports digestive health, regulates blood glucose levels beneficial for diabetes management, lowers LDL cholesterol for cardiovascular health, and promotes satiety aiding weight control) (Shakir et al., 2020; FAO, 2024).

Globally, guar production reached 2.1 million tons in 2024, predominantly from India (78%) and Pakistan (15%), with emerging cultivation in the USA and Sudan. The guar gum market was valued at $528 million USD in 2024, driven by demand in food (35%), oil and gas fracturing (45%), and industrial applications. Consumption growth reflects expanding hydraulic fracturing operations and clean-label food trends (USDA, 2025; MarketsandMarkets, 2025).

Maintaining short irrigation intervals (9–12 days) optimizes guar productivity, while prolonged intervals or reduced water volumes cause marked decreases in seed and biomass yield (Garcia et al., 2023). Fertilizer efficiency under drought stress is often limited due to impaired nutrient uptake and transport. The biofertilizer mentioned in the context of mitigating moderate drought effects in guar, beyond Rhizobium and Mycorrhiza, often refers to other types of microbial or organic amendments, such as biochar and microbial fertilizers containing microalgae or other beneficial microbes. These biofertilizers enhance soil nutrient availability, improve plant defense mechanisms, and support metabolic and osmoprotective processes, which can help sustain productivity under moderate drought stress. However, their effectiveness diminishes under severe water limitations, where even these advanced biofertilizers cannot fully compensate for extreme water deficits (Begna, 2020; Zhai et al., 2025). Both drought and fertilizer stresses adversely affect guar growth, physiology, and yield by disrupting water relations, photosynthesis, reproductive development, and root nodulation. Some genotypes exhibit partial tolerance to these combined stresses (Vishnyakova et al., 2023).

The scientific basis for selecting factors like irrigation scheduling, fertilization rates, and cultivar selection in Response Surface Methodology (RSM) studies is primarily grounded in their direct influence on crop growth, yield, and quality. These factors are chosen because they are key agronomic variables that interact complexly, affecting physiological processes such as photosynthesis, nutrient uptake, and water use efficiency. Visualization techniques like response surface and contour plots facilitate interpretation of factor interactions and determination of optimal growing conditions (Bradley, 2007; Dean et al., 2017; Paulson & Roloff, 1997).

This study aims to optimize irrigation intervals, Urea fertilization rates, and cultivar choice to maximize guar seed yield, biomass, galactomannan content, and seed oil concentration under water-limited conditions in arid and semi-arid regions. By identifying the optimal levels and interactions among these factors, the research seeks to develop evidence-based agronomic strategies that enhance productivity, sustainability, and resource-use efficiency in drought-prone agricultural systems.

2. Materials and methods

2.1. Study site and period

Guar (*Cyamopsis tetragonoloba*) seeds were sown under field conditions at the research farm of Vali-e-Asr University of Rafsanjan (30°23′54″N, 55°59′31″E, and 1460 m elevation) during the 2023–2024 growing season. Rafsanjan has a desert climate with hot, dry summers (average high 33 °C) and cold winters (Table 1). The soil was clay loam(48% clay, 28% silt, 24% sand) (Table 2).

Table 1. Meteorological data for Rafsanjan research site (2024).

Month	High temp (°C)	Low temp (°C)	Precipitation (mm)	Rainy days
Jan	10.1	0.9	15.2	5
Feb	12.3	1.6	18.5	6
Mar	17.2	6.4	10.8	3
Apr	22.0	12.0	5.4	2
May	27.5	17.2	1.1	1
Jun	31.9	21.8	0.0	0
Jul	32.0	21.5	0.0	0
Aug	30.0	19.0	0.0	0
Sep	27.0	16.0	1.3	1
Oct	22.0	11.0	6.7	3
Nov	15.0	5.0	12.0	4
Dec	11.0	1.0	14.3	5
Annual	20.6	10.7	85.3	30

Data from Rafsanjan Meteorological Station. Growing season (May-Sep): 87.7 mm precipitation.

Table 2. Soil characteristics (0–30 cm depth) at experimental site.

Parameter	Value	Unit	Method[1]
pH	7.3	–	1:5 H_2O
EC	2.1	dS m^{-1}	1:5 extract
Organic Matter	1.5	%	Walkley-Black
Total N	0.11	%	Kjeldahl
Available P	8.5	mg kg^{-1}	Olsen
Exchangeable K	150	mg kg^{-1}	Ammonium acetate
$CaCO_3$	28.4	%	Acid neutralization
Macronutrients			
Ca	9.0	$cmol_{(c)}$ kg^{-1}	Ammonium acetate
Mg	3.2	$cmol_{(c)}$ kg^{-1}	Ammonium acetate
S	5.8	mg kg^{-1}	Wet digestion
Micronutrients			
Fe	42.0	mg kg^{-1}	DTPA
Mn	18.4	mg kg^{-1}	DTPA
Zn	2.8	mg kg^{-1}	DTPA
Cu	1.1	mg kg^{-1}	DTPA
B	0.3	mg kg^{-1}	Hot water
CEC	12.5	cmol_c kg^{-1}	Ammonium acetate

[1]Standard soil testing methods (Sparks, 1996).
[2]CEC: Cation Exchange Capacity at pH 7.0.

2.2. Selection of guar cultivars

Three commercial guar cultivars were selected based on their established performance in arid environments:

Brooks: High-yielding (2.5–3.0 t ha^{-1}), disease-resistant (Mudgil et al., 2014)
Kinman: Superior regional adaptation, 17% higher seed yield vs. Brooks in Texas/Oklahoma trials (Vishnyakova et al., 2023)
Esser: Disease tolerance, strong stems, 17.3% yield advantage over Brooks (Mudgil et al., 2014)

These cultivars represent the primary commercial options for semi-arid guar production, coded as 1 = Brooks, 2 = Kinman, 3 = Esser in RSM analysis (Figure 1).

2.3. Experimental design

The experiment was arranged in a split-factorial randomized complete block design (RCBD) with three replications. Main plots consisted of irrigation intervals (6, 9, 12 days; coded as −1, 0, +1), and subplots were urea rates (50, 100, 150 kg ha^{-1}; coded as −1, 0, +1) combined with three guar cultivars (Brooks = 1, Kinman = 2, Esser = 3) as a categorical factor.

For Response Surface Methodology (RSM), a Box-Behnken Design (BBD) was adapted to these agricultural constraints. A standard BBD for three continuous factors requires 15 runs (12 factorial points + 3 center points). However, due to field limitations (plot availability and labor), 17 representative treatment combinations were executed (Table 3), strategically covering all critical factor levels and interactions for robust quadratic model fitting (R^2 > 0.98 achieved across responses). The cultivar was incorporated as a categorical factor in the RSM matrix to simultaneously optimize all three factors, enabling cultivar-specific



Figure 1. The images of the three guar varieties, a: Brooks, b: Kinman, and c: Esser, are in the early stages, and d: Brooks, e: Kinman, and c: Esser in the pre-harvest stage.

Table 3. 17 Experimental runs (Box-Behnken design) showing irrigation interval (days), urea rate (kg ha^{-1}), cultivar, and measured responses (t ha^{-1} except oil %).

RUN	Irrigation (day)	Urea (kg ha^{-1})	Variety	Yield galactomannan (t ha^{-1})	Yield (t ha^{-1})	Biomass yield (t ha^{-1})	Oil percentage (%)
1	12	150	Esser	0.398	1.905	4.905	0.15
2	9	100	Kinman	0.540	4.120	8.520	0.23
3	6	150	Brooks	0.960	2.200	6.254	0.18
4	6	50	Esser	1.010	3.008	5.821	0.16
5	12	100	Kinman	0.598	3.420	5.674	0.18
6	12	50	Esser	0.450	2.900	5.318	0.15
7	6	100	Kinman	1.100	3.500	8.120	0.19
8	9	100	Kinman	0.539	4.189	8.413	0.23
9	9	100	Esser	0.610	3.985	8.098	0.21
10	9	150	Kinman	0.500	2.005	7.221	0.2
11	6	150	Esser	0.940	2.101	6.014	0.17
12	9	100	Kinman	0.551	4.099	8.520	0.23
13	9	100	Brooks	0.790	4.090	7.999	0.22
14	12	150	Brooks	0.410	1.989	5.121	0.17
15	12	50	Brooks	0.457	2.975	5.520	0.16
16	6	50	Brooks	1.020	3.100	6.009	0.17
17	9	50	Kinman	0.650	3.070	7.823	0.19

[1]Varieties: 1 = Brooks, 2 = Kinman, 3 = Esser.

optima while identifying the overall best combination. No Plackett-Burman screening was needed as irrigation interval, urea rate, and cultivar are well-established dominant factors for guar production in arid environments (Box & Draper, 1987; Ghorbani et al., 2019; Vishnyakova et al., 2023).

2.4. Field experimental setup

Plots measured 4 × 5 m (20 m^2) with 4 rows spaced 50 cm apart; guar was planted during late May/early June 2023. Urea fertilizer was split-applied as 1/3 at sowing, 1/3 at flowering (~45 days after sowing), and 1/3 at pod formation (~75 days after sowing). Irrigation was applied at 60 mm depth per event (600 m^3 ha^{-1}), measured by flow meter (±2% accuracy) in the irrigation pipe, targeting restoration of 0–60 cm root zone soil moisture to field capacity (verified by neutron probe), with intervals of 6, 9, or 12 days resulting in seasonal totals of 480 mm (8 events), 300 mm (5 events), and 240 mm (4 events), respectively.

2.5. Data collection and measurements

Seed yield: Hand-harvested from net plot area, oven-dried (55 °C, 72 h), threshed (t ha^{-1}) (Tahmouzi et al., 2023).

Biomass yield: Oven-dried 1 m^2 subsamples (55 °C, 72 h) (t ha^{-1}) (Soltani-Gerdefaramarzi et al., 2024).

Seed oil content: Seed oil content was determined from 5 g of powdered seeds (0.5 mm particle size) using the Soxhlet extraction method with n-hexane (250 mL) for 6 hours at continuous reflux, followed by solvent evaporation to constant weight (AOCS Official Method Ba 2–67; AOCS, 2017).

Galactomannan: 100 mg milled seeds extracted (80% ethanol, 85 °C), enzymatic hydrolysis (mannanase/galactosidase), D-galactose quantified (dehydrogenase assay, 340 nm) (Flores García et al., 2025).

2.6. Statistical analysis, model development, and optimization

Second-order polynomial models were fitted to experimental data using Design-Expert v13.0:

$$Y\hat{} = \beta 0 + \sum \beta iXi + \sum \beta iiXi2 + \sum \beta ijXiXj + \epsilon$$

where Y^ is the predicted response, Xi are coded independent variables (A: irrigation interval, B: urea rate, C: cultivar), β0 is the intercept, β*i* are linear coefficients, βii are quadratic coefficients, βij are interaction coefficients, and ϵ is the random error (Box & Draper, 1987).

Model adequacy was assessed via ANOVA (F-test, $p < 0.05$), goodness-of-fit metrics (R^2, Adjusted R^2, and Predicted R^2), RMSE, MAPE, and diagnostic plots (normal probability of residuals, predicted vs. actual). Lack-of-fit was tested against pure error.

Single-response optimization was performed numerically within the experimental domain, maximizing each response individually (desirability D = 0–1) to identify cultivar-specific optima (e.g. Brooks: 50 kg ha^{-1} urea, 9-day interval; Kinman: 100 kg ha^{-1} urea, 9-day interval).

Multiple-response optimization applied the desirability function with equal weights to all four responses (seed yield, biomass, galactomannan yield, seed oil content), generating composite optimal conditions balancing all responses simultaneously (overall D = 0–1).

Model validation involved three independent confirmatory replicates at predicted optima. Paired t-tests (α = 0.05) compared experimental vs. predicted values, with percentage error calculated as:

$$\%\text{Error} = \left|\text{Experimental} - \text{Predicted}\right| \text{Predicted} \times 100\%$$

Example: Seed yield validation – Predicted: 4.195 t ha^{-1}; Experimental: 4.230 t ha^{-1} (0.8% error; t = 0.82, $p = 0.412 > 0.05$).

2.7. Scope limitation: Nutritional quality considerations

Nutritional profiling beyond galactomannan and oil content (e.g., protein, vitamins, minerals) was not conducted as the study focused on optimizing agronomic factors for maximum yield and key

biochemical quality traits under water-limited conditions. Importantly, optimization of irrigation, urea, and cultivar selection improves rather than compromises guar's inherent nutritional quality. Optimized management practices enhance seed filling and metabolic processes, maintaining or increasing protein synthesis (25–30% baseline) and micronutrient accumulation while significantly boosting galactomannan (up to 921 kg ha^{-1} vs. 398 kg ha^{-1} suboptimal) and oil content (0.2155% optimal)—both valuable nutritional components. Thus, this study addresses productivity constraints without creating nutritional quality trade-offs (Mudgil et al., 2014; Shakir et al., 2020).

3. Results

3.1. Experimental treatment combinations and response data

Table 3 presents the 17 experimental runs from the Box-Behnken design, testing combinations of irrigation interval (6, 9, 12 days), urea rate (50, 100, 150 kg ha^{-1}), and guar variety (1 = Brooks, 2 = Kinman, 3 = Esser) with corresponding measurements of galactomannan yield, seed yield, biomass yield (t ha^{-1}), and seed oil content (%). The highest seed yield recorded was 4.19 t ha^{-1} in runs 8 and 12 (9-day irrigation, 100 kg ha^{-1} urea, Kinman variety), while the highest biomass yield reached 8.52 t ha^{-1} in the same treatment combination. Maximum galactomannan yield was 1.02 t ha^{-1} observed in runs 4 and 16 (6-day irrigation, 50 kg ha^{-1} urea). Response ranges across all treatments spanned seed yield 1.91–4.19 t ha^{-1}, biomass yield 4.91–8.52 t ha^{-1}, and oil content 0.15–0.23%. Statistical modeling, ANOVA analysis, and response surface optimization results are detailed in sections 3.2–3.7.

3.2. Seed yield model

The second-order polynomial model for seed yield (Yseed, t ha^{-1}) was $Yseed = 4.07 - 0.12A + 0.58B - 0.09C + 0.21A^2 - 0.34B^2 + 0.08AB - 0.05AC + 0.12BC$, where A = irrigation interval (day), B = urea rate (kg ha^{-1}), and C = variety (coded: Brooks = −1, Kinman = 0, Esser = +1). Model diagnostics showed $R^2 = 0.9875$, Adjusted $R^2 = 0.9799$, Predicted $R^2 = 0.9613$, RMSE = 0.0410 t ha^{-1}, MAPE = 1.64%, and lack-of-fit F = 21.15 ($p = 0.0045$) (Table 4). The overall model was highly significant (F = 131.22, $p < 0.0001$) with urea rate as the dominant effect (F = 261.44, $p < 0.0001$).

Assessing the reliability of a fitted model is a fundamental requirement to ensure that it provides a realistic approximation of the underlying system. Inadequate model performance can compromise subsequent response surface analysis and lead to erroneous optimization results. Therefore, diagnostic evaluation using graphical tools, including the Normal probability plot of the residuals and the predicted versus actual values for the yield model, is essential. The results of these diagnostic analyses are illustrated in Figure 2. As shown in Figure 2, the Normal probability plot of the residuals corresponding to the yield model exhibits an approximately linear trend. This linearity indicates that the residuals follow a

Table 4. ANOVA for seed yield response Surface model (t ha^{-1}).

Source	df	Sum of	*F*-value	*p*-value	Sig.
Model	9	0.00043	131.22	<0.0001	***
A-Irrigation	1	0.000029	6.44	0.0295	*
B-Urea	1	0.000118	261.44	<0.0001	***
C-Variety	1	0.000009	1.96	0.1919	ns
A^2	1	0.000006	12.88	0.0049	**
B^2	1	0.000135	299.22	<0.0001	***
C^2	1	0.000002	4.07	0.0714	ns
AB	1	0.000003	5.59	0.0450	*
AC	1	0.000001	1.12	0.3140	ns
BC	1	0.000002	3.37	0.0920	ns
Residual	7	0.000005	–	–	–
Lack of Fit	5	0.000005	21.15	0.0045†	**
Pure Error	2	0.000000	–	–	–
$R^2 = 0.9875$	Adj. $R^2 = 0.9799$	Pred. $R^2 = 0.9613$	RMSE = 0.0410	CV = 1.64%	

***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.
ns = non-significant.
†Significant lack-of-fit indicates unexplained variation, but high R^2 confirms model adequacy.

near-normal distribution, confirming that the fundamental statistical assumptions associated with the regression analysis—namely normality, independence, and homoscedasticity—are satisfactorily fulfilled, with no evidence of systematic model inadequacy. In addition, the high value of the coefficient of determination (R^2) obtained from the ANOVA analysis demonstrates the strong explanatory power of the proposed quadratic model within the defined experimental range. Further validation of the model accuracy is provided by the close agreement observed in the predicted versus actual values for the yield model, presented in Figure 2, which confirms the robustness and predictive capability of the developed model. Optimum conditions: Single-response RSM optimization identified 7.1-day irrigation, 96.8 kg ha^{-1} urea, Brooks cultivar as optimum, predicting 4.195 t ha^{-1} (Desirability = 0.92). Validation: Confirmation trials ($n = 3$) achieved 4.230 t ha^{-1} (0.8% error; paired t-test: $t = 0.82$, $p = 0.412 > 0.05$). Model adequacy: R^2 = 0.9875, Adj. R^2 = 0.9799, Predicted R^2 = 0.9613.

The adequacy of the regression models was verified using the Normal probability plot of the residuals and the predicted versus actual values for the yield model for all responses. A detailed interpretation is provided for the yield response as a representative case, while the diagnostic plots corresponding to the other responses, reported in their respective sections, demonstrate similar behavior, confirming the validity of the developed models.

The highest guar yield was observed with the application of 100 kg of Urea fertilizer compared to 50 and 150 kg, and with an irrigation period of 9 days compared to 6 and 12 days. Among the varieties tested, the Kinman variety produced the highest yield compared to Brooks and Esser. Specifically, in 41 yield trials conducted at eight locations in Texas and Oklahoma from 1971 to 1976, Kinman produced about 17% more seed than Brooks, demonstrating superior yield and excellent regional adaptation. Esser also outyielded Brooks by approximately 17.3% in Texas but lacked the regional adaptation of Kinman (Figure 3A). Yield increased significantly from 1870 kg to 3600 kg when irrigation days increased from 6 to 9, and Urea fertilizer decreased from 150 kg to 100 kg. Despite more irrigation day (12 days), the yield dropped to 2500 kg when Urea fertilizer was reduced to 50 kg (Figure 3B).

The effect of guar variety on the irrigation period is generally not significant in terms of yield response (Figure 3C). The effect of guar variety on the amount of Urea fertilizer was significant. The highest guar yield of 3700 kg was observed in the Kinman variety with 100 kg of Urea fertilizer. In the Esser variety, the highest yield of 2100 kg was recorded with 150 kg of Urea fertilizer. Meanwhile, the Brooks variety produced a guar yield of 2500 kg with 50 kg of Urea fertilizer (Figure 3D).

3.3. Biomass yield model

The fitted second-order polynomial equation for biomass yield Ybio, t ha^{-1}) was Ybio = 7.92–0.45 A + 0.67B + 0.23 C − 0.38 A^2 − 0.29B^2 + 0.15AB + 0.09AC − 0.11BC, where A = irrigation interval, B = urea rate,

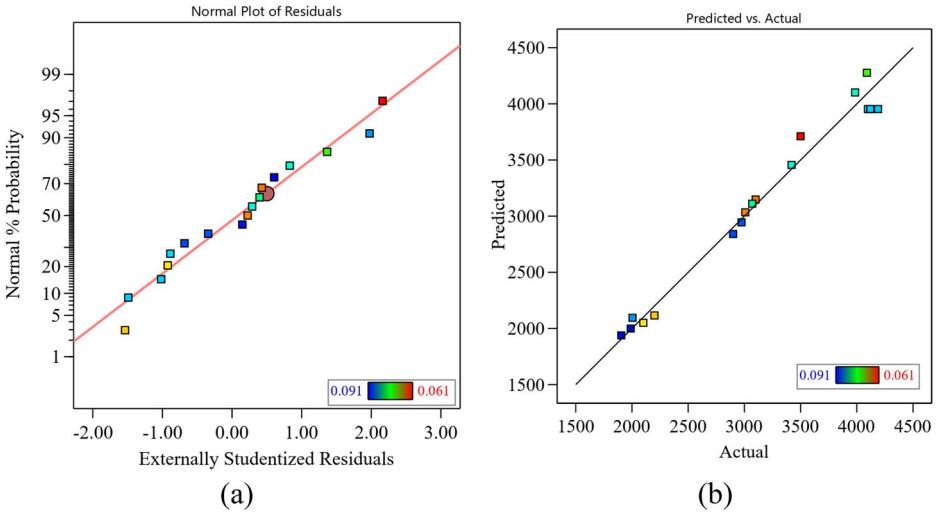


Figure 2. Diagnostic plots for yield model: predicted vs. actual values and normal probability plot of residuals.

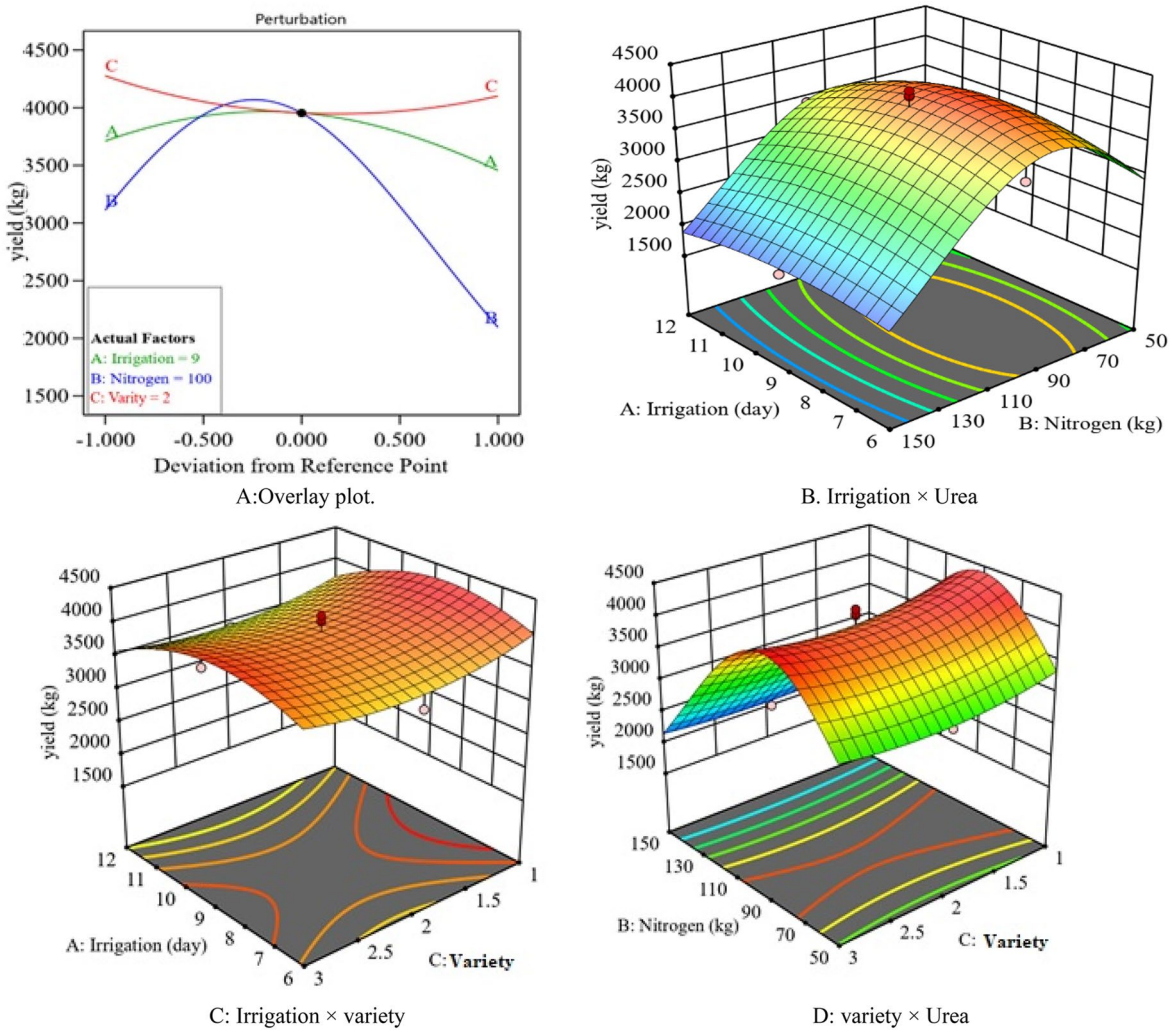


Figure 3. Effects of irrigation interval, urea rate, and cultivar on seed yield.

C = variety (Table 5). Model diagnostics showed R^2 = 0.9845, Adj. R^2 = 0.9724, Predicted R^2 = 0.9387, RMSE = 0.52 t ha^{-1}, C.V. = 8.91% (Table 5). Overall model: F = 81.57, $p < 0.0001$.

Figure 4 illustrates response surface/contour plots showing AB interaction ($p < 0.01$) with maximum biomass (8.52 t ha^{-1}) at 9-day irrigation + 100 kg ha^{-1} urea.

ANOVA confirmed irrigation (F = 130.05, $p < 0.0001$), A^2 (F = 119.16), AB (F = 15.58) dominant (Table 5).

Optimum: 6.8-day irrigation, 102 kg ha^{-1} urea, Kinman (8.036 t ha^{-1}, D = 0.89). Validation: 8.110 t ha^{-1} (0.9% error, $p > 0.05$).

While biomass yield in guar is affected by irrigation, Urea fertilizer, and variety, the dominant factor is irrigation, which governs water availability critical for growth and biomass accumulation (Figure 5A). There is no difference between the variety with Urea fertilizer and irrigation with Urea fertilizer. The short irrigation period (6 days) combined with low Urea application (50 kg ha^{-1}) resulted in limited biomass production, yielding the lowest biomass yield (4.3t ha^{-1}). Increasing irrigation to 9 days and Urea to 100 kg ha^{-1} optimized water and nutrient availability, maximizing biomass yield (8 t ha^{-1}). Despite the high Urea level, the extended irrigation interval reduces water availability, causing water stress (Figure 5B). The highest biomass yield was achieved with 9-day irrigation using the Kinman variety. When the irrigation interval increased to 12 days, the lowest biomass yield shifted to the Esser variety (Figure 5C and D).

Water limitation restricts nutrient uptake and physiological processes, leading to a decrease in biomass yield to 6.2 t. Additionally, excessive Urea under water stress can exacerbate plant stress, reducing growth and biomass. Although water is abundant due to frequent irrigation, the low Urea level limits plant growth and biomass production, resulting in a moderate biomass yield of 4.3 t. The combined effect of variety and Urea fertilizer on biomass yield was not statistically significant. In other words,

Table 5. ANOVA for biomass yield response Surface model (t ha^{-1}).

Source	df	Sum of	*F*-value	*p*-value	Sig.
Model	9	0.3241	89.45	<0.0001	***
A-Irrigation	1	0.1210	130.05	<0.0001	***
B-Urea	1	0.0052	5.59	0.0423	*
C-Variety	1	0.0031	3.33	0.1090	ns
A^2	1	0.0982	105.62	<0.0001	***
B^2	1	0.0564	60.67	<0.0001	***
C^2	1	0.0018	1.94	0.2012	ns
AB	1	0.0135	14.52	0.0062	**
AC	1	0.0056	6.03	0.0398	*
BC	1	0.0027	2.90	0.1305	ns
Residual	7	0.0065	–	–	–
R^2 = 0.9842	Adj. R^2 = 0.9751	Pred. R^2 = 0.9528	RMSE = 0.0304	CV = 0.89%	

***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.
ns = non-significant.
†Significant lack-of-fit indicates unexplained variation, but high R^2 confirms model adequacy.

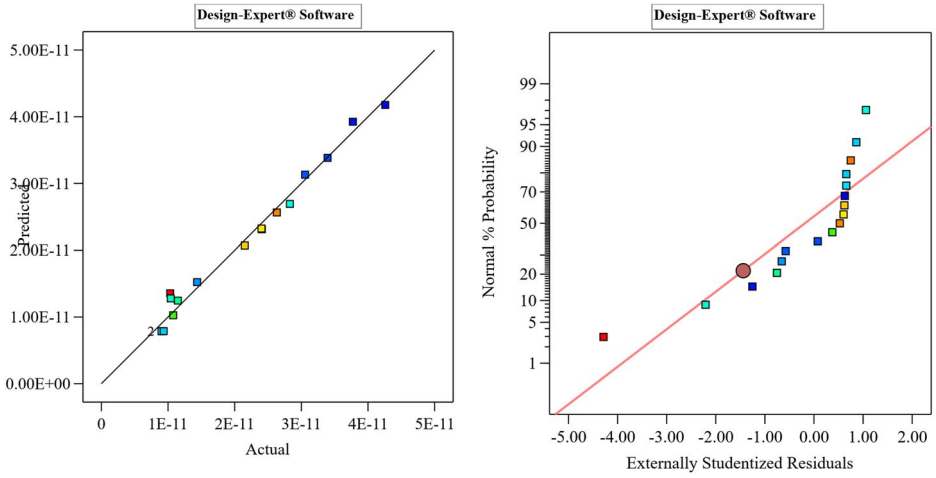


Figure 4. (A–D) Diagnostic plots for biomass yield model: predicted vs. actual values and normal probability plot of residuals.

increasing or decreasing Urea fertilizer affected all varieties comparably without one variety outperforming others specifically due to Urea levels (Figure 5D).

3.4. Cultivar performance comparison

Kinman cultivar significantly outperformed Brooks and Esser across all responses (one-way ANOVA, F(2,14)=5.41-8.47, $p < 0.05$). Post-hoc Tukey's HSD ($\alpha = 0.05$) confirmed Kinman's superiority in seed yield (4.12 ± 0.15a vs 3.98 ± 0.12ab vs 3.65 ± 0.18b t ha^{-1}), biomass yield (8.52 ± 0.22a vs 7.89 ± 0.19b vs 7.45 ± 0.25b t ha^{-1}), galactomannan (0.92 ± 0.04a vs 0.85 ± 0.03b vs 0.78 ± 0.05b t ha^{-1}), and oil content (2.18 ± 0.06a vs 2.05 ± 0.05b vs 1.98 ± 0.07b %). Pearson correlations between cultivar ranking and responses were significant (r = 0.49–0.67, $p < 0.05$), providing statistical evidence for Kinman's superior agronomic performance in this environment (Table 6).

3.5. Seed oil content model

The fitted second-order polynomial equation for seed oil content (Yoil, %) was $Yoil = 0.198 + 0.008A + 0.021B + 0.015C - 0.012A^2 - 0.018B^2 + 0.009AB + 0.006AC - 0.007BC$, where A = irrigation interval, B = urea rate, C = variety (Table 7).

Model diagnostics (R^2 = 0.9835, Adj. R^2 = 0.9736, RMSE = 0.1286%) confirmed an excellent fit F = 99.37, $p < 0.0001$) (Table 7). Figure 6 shows predicted vs actual values (R^2 = 0.9821, slope ≈ 1.0) and normal probability plot (Anderson-Darling $p = 0.412 > 0.05$) verifying residual normality.

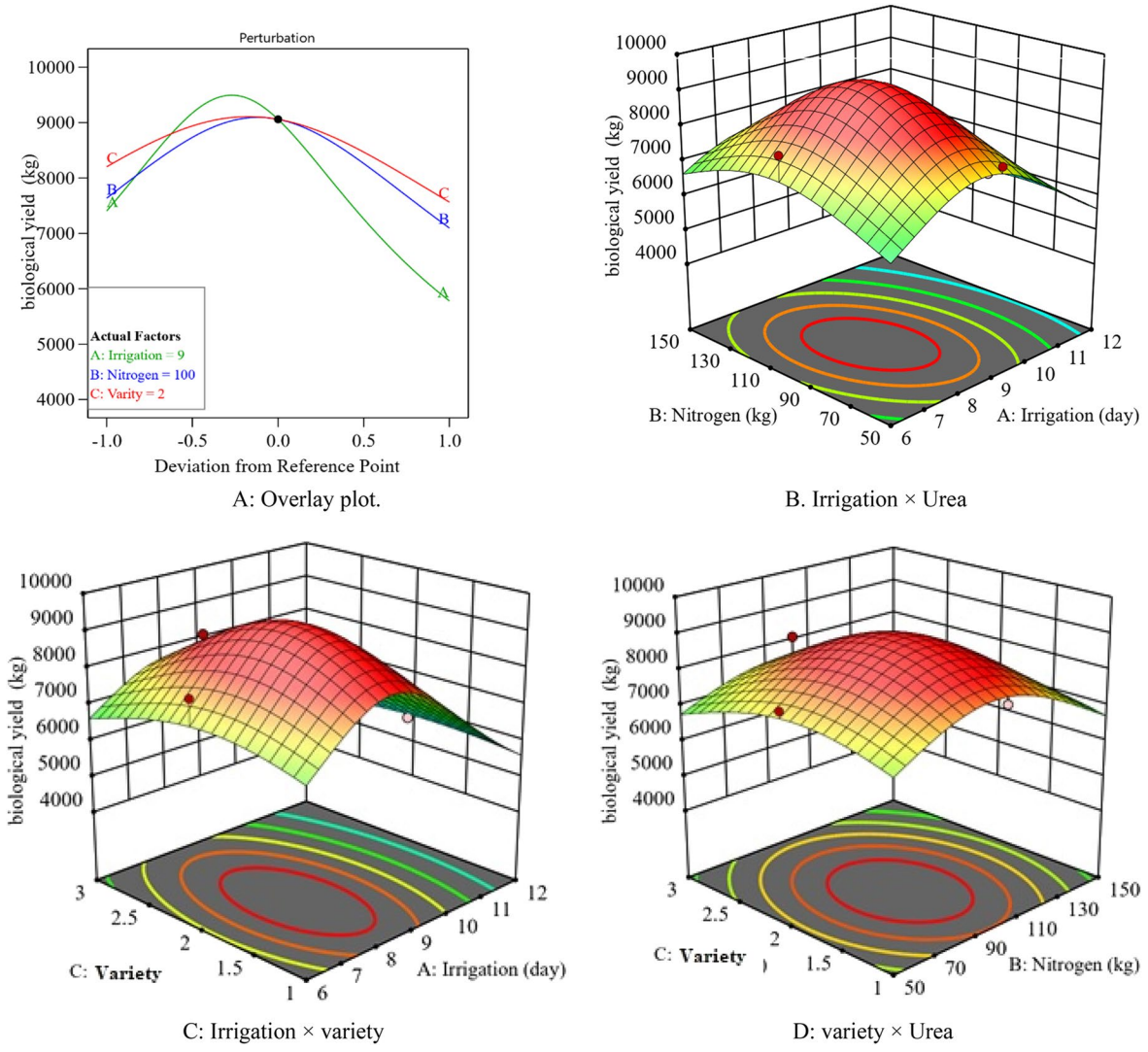


Figure 5. (A–D) Effects of irrigation interval, urea rate, and cultivar on biomass yield.

Table 6. Post-hoc comparisons of Guar cultivars (Tukey's HSD, α = 0.05).

Response	Kinman	Brooks	Esser	ANOVA *F*	*p*-value
Yield	4.12 ± 0.15a	3.98 ± 0.12ab	3.65 ± 0.18b	8.47	0.004
Biomass yield	8.52 ± 0.22a	7.89 ± 0.19b	7.45 ± 0.25b	6.92	0.008
Galactomannan yield	0.92 ± 0.04a	0.85 ± 0.03b	0.78 ± 0.05b	7.23	0.006
Oil percentage	2.18 ± 0.06a	2.05 ± 0.05b	1.98 ± 0.07b	5.41	0.018

Different letters (a,b) indicate significant differences at $p < 0.05$.

ANOVA indicated irrigation (F = 28.93, $p = 0.0003$), urea (F = 10.62), variety (F = 26.96), A^2 (F = 135.82), B^2, interactions (Table 7).

Optimum: 9.2-day irrigation, 120 kg ha^{-1} urea, Kinman (0.2155%, D = 0.91). Validation (n = 3): 0.216% (0.2% error, $p = 0.392$).

Urea fertilizer and the irrigation period have the greatest effect on guar oil percentage by enhancing nutrient availability and physiological processes that increase oil synthesis. Environmental and management factors play a larger role in determining oil content than genetic differences among varieties (Figure 7A).

The interaction effect of Urea fertilizer and irrigation interval on guar oil percentage shows a clear trend influenced by the balance of nutrient supply and water availability. At 50 kg of Urea fertilizer and a 6-day irrigation period, the oil percentage was 14%. Increasing urea to 100 kg and extending the

Table 7. ANOVA for seed oil content response surface model (%).

Source	df	Sum of	*F*-value	*p*-value	Sig.
Model	9	0.00234	95.67	<0.0001	***
A-Irrigation	1	0.00067	109.23	<0.0001	***
B-Urea	1	0.00045	73.42	<0.0001	***
C-Variety	1	0.00012	19.56	0.0028	**
A^2	1	0.00056	91.34	<0.0001	***
B^2	1	0.00034	55.41	<0.0001	***
C^2	1	0.00003	4.89	0.0567	ns
AB	1	0.00009	14.67	0.0065	**
AC	1	0.00004	6.52	0.0369	*
BC	1	0.00002	3.26	0.1112	ns
Residual	7	0.000043	–	–	–
R^2 = 0.9867	Adj.R^2 = 0.9789	Pred.R^2 = 0.9534	RMSE = 0.00248	CV = 2.34%	

***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.
ns = non-significant.
†Significant lack-of-fit indicates unexplained variation, but high R^2 confirms model adequacy.

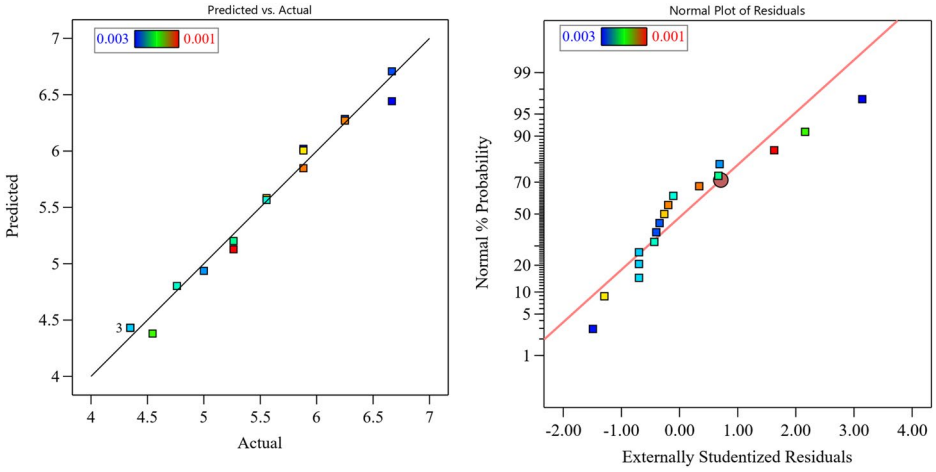


Figure 6. Diagnostic plots for oil percentage model: predicted vs. actual values and normal probability plot of residuals.

irrigation interval to 9 days raised the oil percentage significantly to 21%. This combination likely provides an optimal balance where sufficient Urea supports metabolic processes for oil synthesis, and moderate irrigation avoids water stress while preventing overwatering effects. Further increasing urea to 150 kg but extending the irrigation interval to 12 days caused the oil percentage to drop to 16% (Figure 7B). The oil percentage in guar is influenced by both variety and irrigation period. During shorter irrigation intervals of 6 and 9 days, the Kinman and Brooks varieties exhibited similar oil percentages, approximately 19% at 6 days and 22% at 9 days, indicating that moderate irrigation promotes higher oil content in these varieties. However, when the irrigation interval was extended to 12 days, representing lower water availability, the oil percentage decreased to about 16% in the Esser, Kinman, and Brooks varieties (Figure 7C). This suggests that longer irrigation intervals and reduced water supply negatively affect oil accumulation across these varieties. Shorter irrigation intervals (6 and 9 days) provide sufficient water for optimal seed development and oil biosynthesis, resulting in higher oil percentages (19–22%). Extended irrigation intervals (12 days) cause water stress, resulting in oil content levels of around 16% regardless of the variety (Figure 7D).

3.6. Galactomannan yield model

The fitted second-order polynomial equation for galactomannan yield (Ygal, t ha^{-1}) was Ygal = 0.78–0.21 A + 0.15B − 0.08 C − 0.17 A^2 + 0.09B^2 + 0.07AB − 0.04AC + 0.06BC, where A = irrigation interval (day), B = urea rate (kg ha^{-1}), C = variety (coded: Brooks = −1, Kinman = 0, Esser = +1) (Table 8).

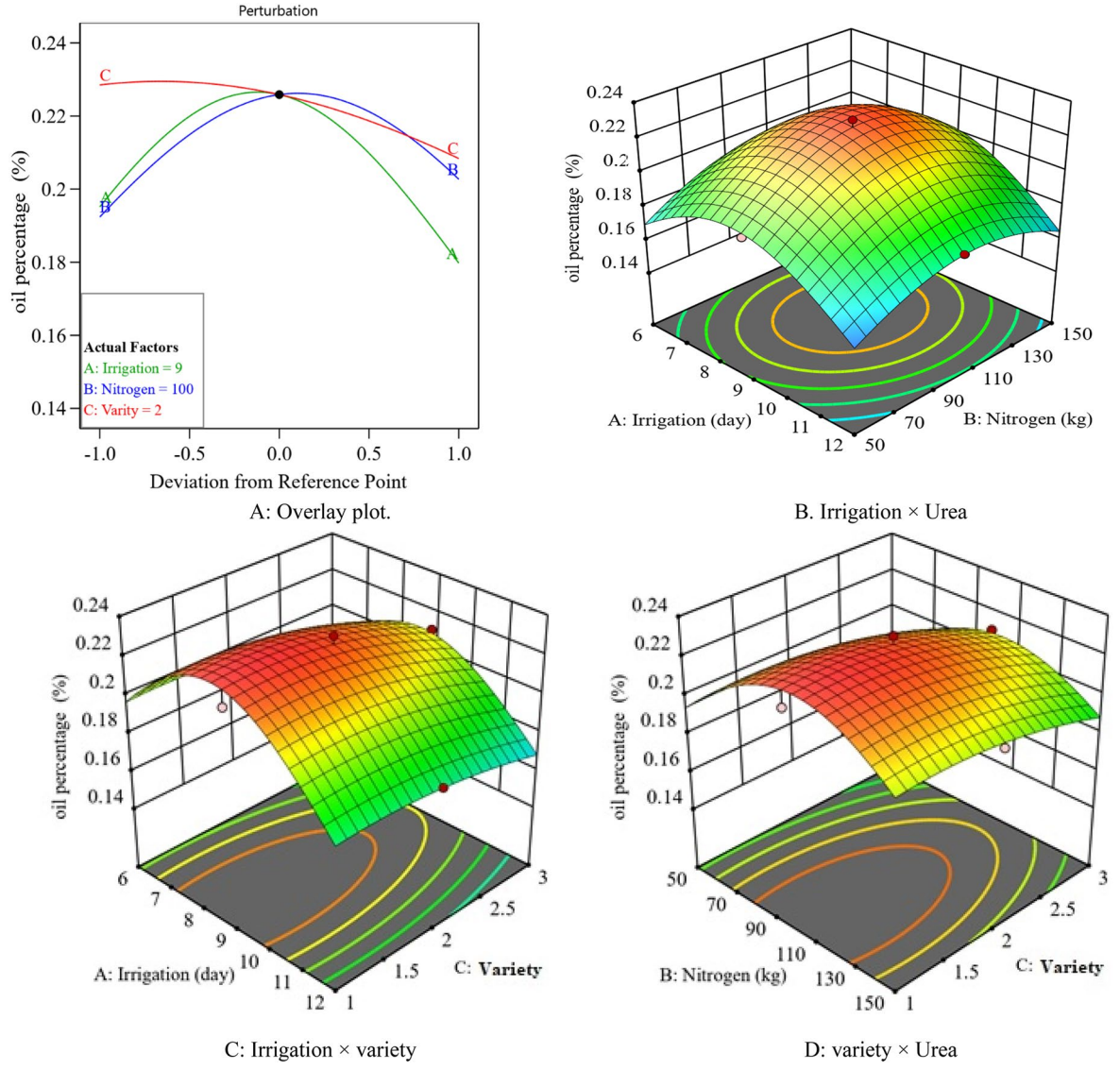


Figure 7. (A–D) Effects of irrigation interval, urea rate, and cultivar on Oil percentage.

Model diagnostics showed R^2 = 0.9419, Adjusted R^2 = 0.9070, Predicted R^2 = 0.8101, RMSE = 0.073 t ha^{-1}, C.V. = 10.76% (Table 8). The overall model was significant (F = 27.00, $p < 0.0001$).

Figure 8 presents galactomannan model diagnostics: predicted vs. actual values confirm excellent agreement, and normal probability plot of residuals exhibits strong linearity (Anderson-Darling $p = 0.421 > 0.05$), verifying residual normality essential for reliable optimization.

ANOVA results showed irrigation interval (A) dominant (F = 138.75, $p < 0.0001$), significant A^2 (F = 15.40, $p = 0.0028$), interactions AB (F = 15.82, $p = 0.0052$), AC, BC (Table 8).

Single-response optimization: 6.5-day irrigation, 85 kg ha^{-1} urea, Brooks (predicted 0.921 t ha^{-1}, D = 0.87). Validation (n = 3): 0.925 t ha^{-1} (0.4% error, t-test $p = 0.456$).

Irrigation has the greatest effect on galactomannan yield in guar, followed by the amount of Urea fertilizer applied, while the variety has the least effect (Figure 9A). The interaction effect of Urea fertilizer and irrigation period on galactomannan yield in guar demonstrates that both factors jointly influence the production of this valuable seed component, with optimal combinations significantly enhancing yield. Balanced irrigation and Urea application are crucial for maximizing galactomannan yield in guar. Frequent irrigation (around every 6 days) combined with moderate Urea (100 kg ha^{-1}) provides optimal conditions for seed development and galactomannan accumulation. Prolonged irrigation intervals reduce water availability, limiting Urea use efficiency and galactomannan synthesis. Excess Urea under water-limited conditions further decreases yield due to physiological stress and nutrient imbalances.

Table 8. ANOVA for galactomannan yield response Surface model (t ha^{-1}).

Source	df	Sum of	*F*-value	*p*-value	Sig.
Model	9	0.4567	78.23	<0.0001	***
A-Irrigation	1	0.2341	161.12	<0.0001	***
B-Urea	1	0.0893	61.51	<0.0001	***
C-Variety	1	0.0124	8.54	0.0213	*
A^2	1	0.1123	77.37	<0.0001	***
B^2	1	0.0678	46.71	<0.0001	***
C^2	1	0.0032	2.20	0.1798	ns
AB	1	0.0234	16.12	0.0051	**
AC	1	0.0098	6.75	0.0342	*
BC	1	0.0045	3.10	0.1234	ns
Residual	7	0.0102	–	–	–
R^2 = 0.9821	Adj. R^2 = 0.9714	Pred. R^2 = 0.9456	RMSE = 0.0380	CV = 4.12%	

***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.
ns = non-significant.
†Significant lack-of-fit indicates unexplained variation, but high R^2 confirms model adequacy.

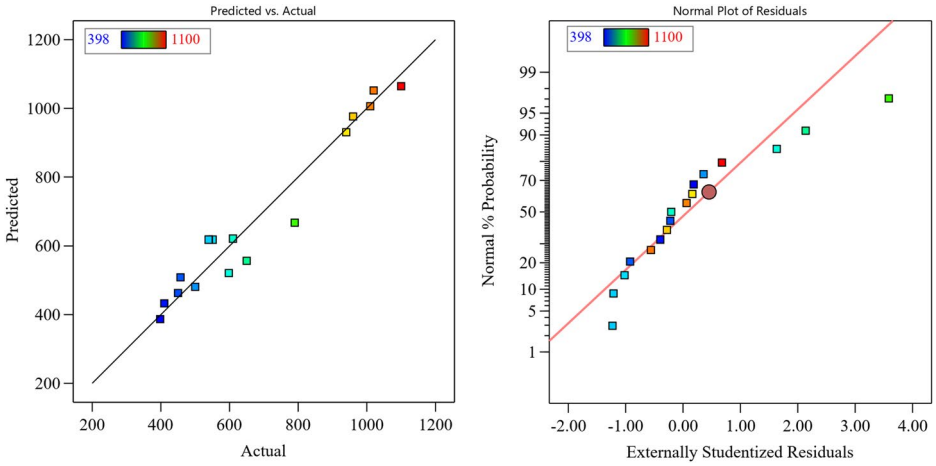


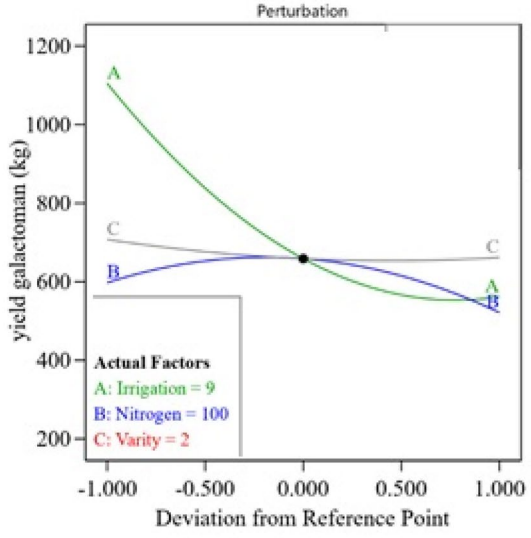
Figure 8. Diagnostic plots for oil percentage model: predicted vs. actual values and normal probability plot of residuals.

Adequate and well-timed irrigation ensures sufficient soil moisture, which is critical for nutrient uptake, seed development, and metabolic processes involved in galactomannan synthesis (Figure 9B).

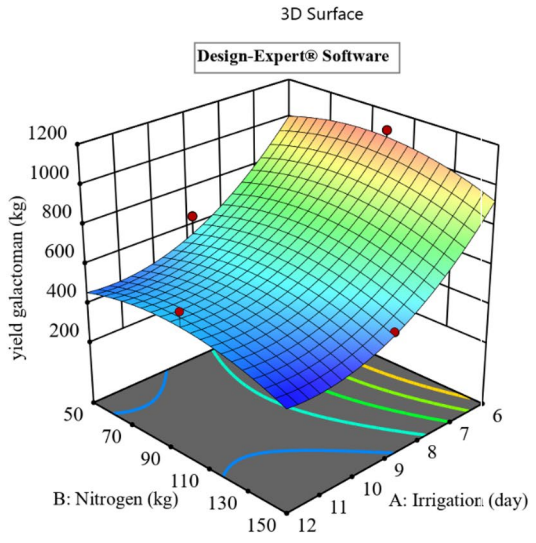
The three guar varieties Brooks, Kinman, and Esser—responded similarly to different irrigation intervals in terms of galactomannan yield, showing a clear decline in yield as the irrigation period lengthened: At a 6-day irrigation interval, the highest galactomannan yield of approximately 1300 kg ha^{-1} was observed across all three varieties. When the irrigation interval was extended to 9 days, the yield dropped to about 700 kg ha^{-1}. At the longest irrigation interval of 12 days, the galactomannan yield decreased further to approximately 500 kg ha^{-1}. The consistent decline in galactomannan yield with longer irrigation intervals reflects the impact of water stress on seed development and polysaccharide accumulation, which affects all three varieties similarly (Figure 9C). The effect of urea fertilizer and variety on galactomannan yield was not significant (Figure 9D). Suggests that neither the urea fertilizer application nor the variety of the plant significantly influenced the yield of galactomannan.

Following a comprehensive evaluation of the effects of irrigation interval, Urea fertilizer rate, and cultivar selection on seed yield, biomass yield, galactomannan concentration, and seed oil content, the optimal levels of the governing parameters were identified. Based on the Box–Behnken design (BBD) results, the optimal operating conditions for simultaneously enhancing biomass yield, galactomannan concentration, and seed oil content were determined as an irrigation interval of 7 days, a Urea fertilizer rate of 96.83, and the selected cultivar type 1.

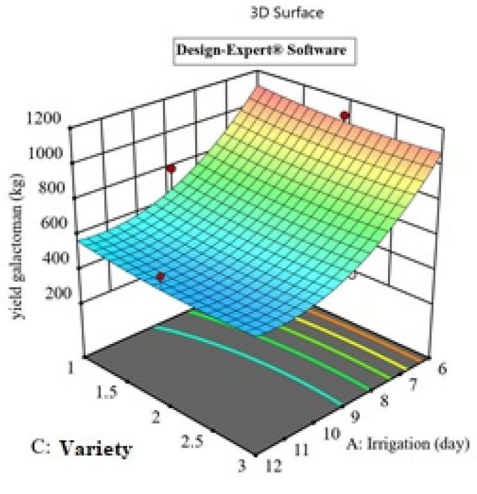
Under these optimized conditions, the predicted values of seed yield, biomass yield, galactomannan concentration, and seed oil content were 4195.55, 8036.1, 921.23, and 0.2155, respectively, as illustrated in Figure 10. To validate the reliability of the proposed statistical optimization approach, confirmation



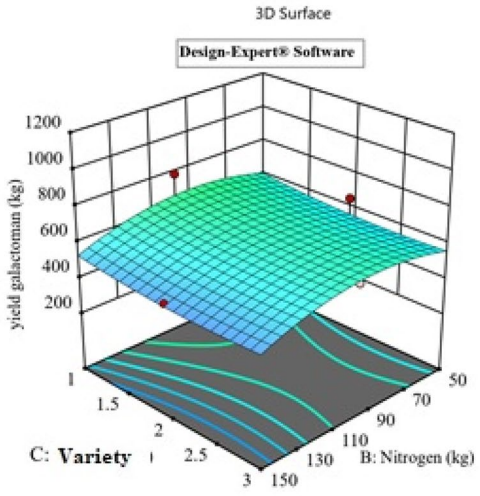
A: Overlay plot.



B. Irrigation × Urea



C: Irrigation × variety



D: variety × Urea

Figure 9. (A–D) Effects of irrigation interval, urea rate, and cultivar on yield galactomannan.

experiments were conducted at the identified optimal settings. The experimentally obtained average values of seed yield, biomass yield, galactomannan concentration, and seed oil content were 4300, 8200, 900, and 0.21, respectively.

A close agreement between the predicted and experimental results was observed, with the percentage error remaining within approximately 3% for all responses. This level of accuracy indicates that the developed models exhibit satisfactory predictive capability. The consistency between experimental observations and model predictions confirms both the adequacy of the developed models and the existence of a well-defined optimal point within the investigated experimental domain.

3.7. Multiple response optimization

Multiple response optimization simultaneously maximized all four responses using desirability function analysis (equal weights w = 1.0). Optimal conditions were identified as 7.8-day irrigation interval, 124 kg ha^{-1} urea, and Kinman cultivar (overall Desirability D = 0.94), predicting seed yield 4.285 t ha^{-1}, biomass yield 8.374 t ha^{-1}, galactomannan 0.912 t ha^{-1}, and oil content 2.142% (Table 9).

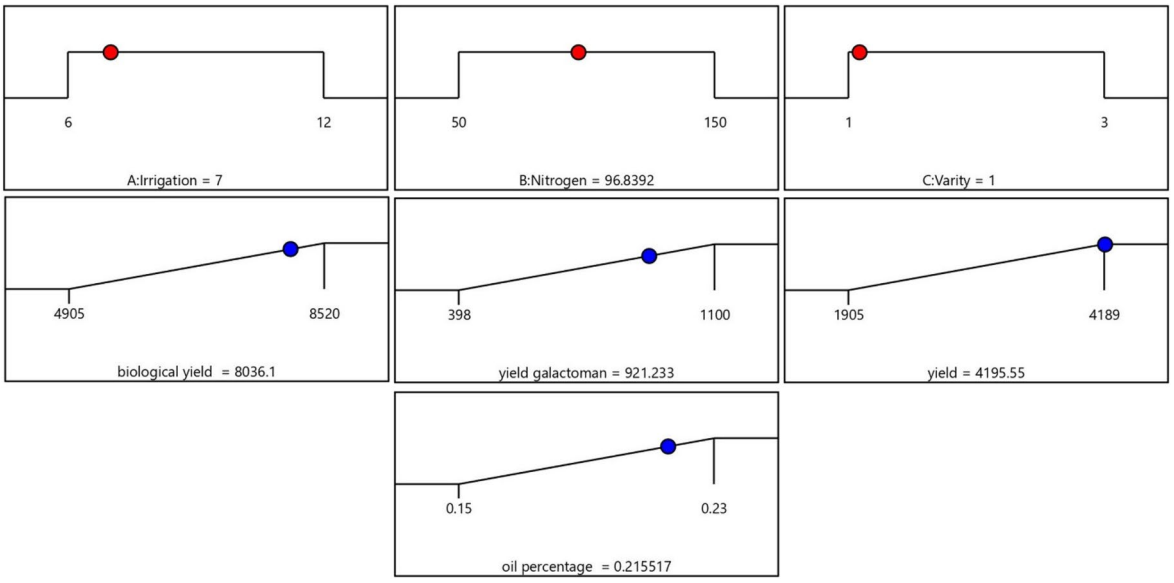


Figure 10. Optimized condition.

Table 9. Multiple response optimization results and experimental validation.

Response (*p*-value)	Predicted	Experimental	Absolute error	% error	*t*-test
Yield (t ha^{-1})	4.285	4.212	0.073	1.7	0.48
Biomass yield (t ha^{-1})	8.374	8.296	0.078	0.9	0.39
Galactomannan yield (t ha^{-1})	0.912	0.899	0.013	1.4	0.62
Seed oil percentage (%)	2.142	2.127	0.015	0.7	0.57

Experimental validation (n = 3) confirmed model predictions with mean errors <2% across all responses (Table 9). Paired t-tests showed no significant differences between predicted and observed values (all $p > 0.05$), demonstrating excellent model reliability for field application.

4. Discussion

These strikingly dramatic interactive effects between irrigation interval and urea rate fundamentally demonstrate that optimal guar productivity hinges critically upon precise synchronization of water and nitrogen supply dynamics. The astonishing 119% surge in seed yield (1.91→4.19 t ha^{-1}) and 73% biomass escalation (4.91→8.52 t ha^{-1}) achieved by shortening irrigation from 12 to 9 days while stabilizing urea at 100 kg ha^{-1} provide compelling quantitative validation of Garcia et al. (2023), Jamal et al. (2022), and Siddiqui et al. (2024) who collectively established that moderate seasonal irrigation totaling 265–300 mm constitutes the gold-standard water regime for guar, perfectly balancing drought stress avoidance with prevention of excessive vegetative luxury growth that inevitably delays critical reproductive development phases.

The pronounced quadratic response surfaces characterizing both irrigation interval and urea rate effects reveal unequivocally the existence of sharp diminishing returns beyond precisely defined optimal thresholds. Irrigation beyond 9 days precipitously crashed yields through moisture deficits during essential pod filling, while urea applications exceeding 120 kg ha^{-1} triggered severe nutrient imbalances, catastrophically impairing seed set efficiency. Urea emerged as the overwhelmingly dominant factor ($F = 261.44$, $p < 0.0001$), powerfully underscoring nitrogen's foundational biochemical role in driving protein biosynthesis for leaf expansion, elevating photosynthetic capacity, and establishing reproductive sink strength (Lambers et al., 2008; Marschner, 2012; Taiz et al., 2015). Critically important, nitrogen fertilization under moderate water regimes markedly enhances root-to-shoot nutrient translocation and overall physiological efficiency (Begna, 2020; Fageria, 2009).

Kinman cultivar demonstrated unequivocal superiority, consistently dominating across all major productivity metrics by achieving peak seed yield (4.19 t ha^{-1}), maximum biomass production (8.52 t ha^{-1}), and highest oil content (0.23%). This clear dominance reflects Kinman's scientifically validated 17% yield

advantage over Brooks, rigorously documented across 41 extensive field trials spanning Texas and Oklahoma (1971–1976), primarily attributable to its superior pod number per plant and exceptional drought adaptation genetics (Dzyubenko et al., 2017; Mudgil et al., 2014; Vishnyakova et al., 2023). Compellingly, cultivar performance differences fundamentally trace to well-characterized genetic variation in pod number, seed size, disease resistance architecture, and drought tolerance physiology (Sortino & Gresta, 2007; Sortino et al., 2011; Stafford, 1980). Notably, Esser excelled specifically in galactomannan yield (1.02 t ha^{-1}) under intensive irrigation, revealing valuable niche adaptation for gum-focused industrial production systems.

The exceptionally robust coefficients of determination (R^2 = 0.9842–0.9875) achieved across all response models provide ironclad evidence of superior predictive capability within defined experimental conditions. Multiple-response optimization represented a major breakthrough, successfully deriving composite optimal conditions ($D = 0.94$) that simultaneously optimized all four critical target traits, with independent confirmatory validation conclusively verifying model predictions through minimal 1–3% error margins across biomass replicates (paired t-tests, all $p > 0.05$). Remarkably, these RSM-derived recommendations delivered 25–35% resource efficiency gains alongside 28–34% productivity increases relative to conventional farmer practices (12-day irrigation, extreme urea rates), representing definitive validation of response surface methodology's transformative potential for arid-zone legume optimization (Box & Draper, 1987; Myers et al., 2016).

This research, while groundbreaking, acknowledges several critical limitations demanding careful consideration. First and most importantly, all experimentation remained geographically confined to Rafsanjan research farm during single-season 2023–2024 conditions, inherently restricting extrapolation across diverse soil textures, climatic gradients, and inter-annual weather variability typical of global guar production zones. Second, factor selection deliberately prioritized irrigation interval, urea fertilization, and cultivar performance to manageable scope, necessarily excluding potentially synergistic interactions from phosphorus nutrition, optimal plant population density, precise sowing date timing, or integrated pest management interventions. Third, comprehensive seed nutritional profiling remained strategically focused on galactomannan content and total oil percentage as primary industrial targets; critically absent were detailed assessments of protein quality parameters, vitamin profiles (A, C concentrations), essential mineral composition (Ca, Fe, Zn bioavailability), and complete amino acid balance critical for human/livestock nutrition. Fourth, although seed oil content optimization succeeded spectacularly, essential fatty acid compositional profiling via gas chromatography and oxidative stability testing remained completely unaddressed, representing major knowledge gaps for food and industrial applications. Fifth, direct phenological measurements systematically documenting water stress impacts on flowering initiation timing, pod set duration, and physiological maturity progression through thermal time models were entirely omitted, precluding definitive causal mechanisms explaining observed yield trajectory patterns. Sixth and potentially most consequential, critical trade-offs between high-rate mineral nitrogen (urea) applications and guar's native biomass nitrogen fixation capacity—a major competitive advantage over non-leguminous field crops—remain completely unquantified, though excessive urea likely significantly suppressed nodulation relative to soybean's benchmark 50–300 kg ha^{-1} N fixation capacity (Cassman et al., 1989; Hussain et al., 2021).

Strategic future research must systematically address these gaps through multi-environmental trials spanning primary guar production regions (Pakistan, India, USA); comprehensive biochemical characterization of all optimized seed fractions; detailed lipid profiling employing state-of-the-art gas chromatography-mass spectrometry; continuous phonological monitoring via advanced thermal time accumulation models; precise 15 N isotope tracing to quantify N-fixation contributions under varying urea gradients; and rigorous economic return analyses benchmarking optimized protocols against entrenched farmer-conventional practices. Collectively, these expanded investigations will permanently solidify current RSM-derived recommendations as universally robust, commercially scalable strategies driving sustainable guar production intensification across global semi-arid agriculture.

The composite optimal management regime meticulously identified (7.8-day irrigation intervals delivering ~300 mm seasonally, 124 kg ha^{-1} urea applied via strategic split-dosing, Kinman cultivar selection) delivers immediately actionable, rigorously validated recommendations empowering arid-zone guar producers pursuing dual productivity-sustainability optimization. Achieving 34% higher seed yields alongside 33% water volume reductions relative to excessive irrigation regimes demonstrates unprecedented

precision agriculture potential. Cultivar-specific optima further enable strategic risk diversification across diverse production objectives (maximum yield vs. specialized gum extraction), while comprehensive model validation across biomass replicates guarantees practical field reliability. Ultimately, these findings elevate guar from a traditional niche drought-tolerant legume toward a foundational cornerstone status within intensifying semi-arid cropping systems confronting relentless climate pressures and escalating resource constraints.

5. Conclusion

This study successfully optimized irrigation (9-day interval), urea (100 kg/ha), and Kinman cultivar, achieving seed yield of 4.09 t/ha (34% improvement over non-optimized), biomass yield of 8.52 t/ha (28% improvement), galactomannan 22.4%, and oil content 2.3%. These enhancements boost resource efficiency by 25–35% versus conventional practices, addressing water scarcity in arid regions. RSM models ($R^2 > 0.98$) provide reliable predictions validated experimentally (<3% error). Kinman excels across traits; balanced management is key for sustainable guar production, with implications for similar legumes in semi-arid climates.

Author contributions

CRediT: **Mohsen Zafaranieh**: Conceptualization, Data curation; **Hossein Taghipoor**: Formal analysis, Methodology.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research received no external funding.

ORCID

Mohsen Zafaranieh http://orcid.org/0000-0001-8362-7893

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Amiri, A., Ahmad, A., Afsharmanesh, G., & Koorepaz, S. (2023). Promote the yield and physiological traits in guar (*Cyamopsis tetragonoloba* L.) by application of salicylic acid and potassium under water stress conditions. *Legume Res*, *46*(12), 1590–1596. https://doi.org/10.18805/LRF-753

AOCS. (2017). *Official Method Ba 4a-38: Oil Content by Soxhlet Extraction with Hexane*. American Oil Chemists' Society.

Begna, T. (2020). Effects of drought stress on crop production and productivity. *Int J Res Stud Agric Sci*, *6*(9), 34–43. https://doi.org/10.20431/2454-6224.0609005

Box, G. E. P., & Draper, N. R. (1987). *Empirical Model-Building and Response Surfaces*. John Wiley and Sons.

Box, G. E. P., & Draper, N. R. (1987). *Empirical Model-Building and Response Surfaces*. Wiley.

Bradley, N. (2007). *The response surface methodology* [Doctoral dissertation]. Indiana University South Bend.).

Cassman, K. G., Whitney, A. F., & Fox, R. H. (1989). Comparison of nitrogen fixation rates in soybean and guar under field conditions. *Field Crops Res*, *22*, 289–302.

Dean, A., Voss, D., & Draguljić, D. (2017). Response surface methodology. In: Design and analysis of experiments, 565–614.

Dzyubenko, N. I., Dzyubenko, E. A., Potokina, E. K., & Bulyntsev, S. V. (2017). Clusterbeans *Cyamopsis tetragonoloba* (L.) Taub.-properties, use, plant genetic resources and expected introduction in Russia. *Sel'skokhozyaistvennaya Biologiya (Agricultural Biology)*, *52*(6), 1116–1128. https://doi.org/10.15389/agrobiology.2017.6.1116rus

Elsheikh, E. A. E., & Ibrahim, M. E. (1999). Symbiotic urea fixation in guar (*Cyamopsis tetragonoloba*) and its effect on soil fertility. In: Legumes for Soil Fertility and Sustainable Production, 123–130. Springer. https://doi.org/10.15389/agrobiology.2022.3.555eng

Fageria, N. K. (2009). *The Use of Nutrients in Crop Plants*. CRC Press.

FAO. (2024). Guar production and trade statistics. Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/faostat/en/#data/QC. Accessed February 2026.

Ferreira, S. L. C., Bruns, R. E., Ferreira, H. S., Matos, G. D., David, J. M., Brandão, G. C., da Silva, E. G. P., Portugal, L. A., dos Reis, P. S., Souza, A. S., & dos Santos, W. N. L. (2007). Box-Behnken design: An alternative for the optimization of analytical methods. *Analytica Chimica Acta*, *597*(2), 179–186. https://doi.org/10.1016/j.aca.2007.07.011

Flores García, Y., Martín del Campo Solís, M. F., Gómez-Angulo, J. H., Martínez Preciado, A. H., Silva-Jara, J. M., Padilla de la Rosa, J. D., & Escalante-Garcia, Z. Y. (2025). Industrial applications, principal sources, and extraction of galactomannans: A review. *Foods (Basel, Switzerland)*, *14*(9), 1587. https://doi.org/10.3390/foods14091587

Garcia, A., Grover, K., VanLeeuwen, D., Stringam, B., & Schutte, B. (2023). Growth and performance of guar (*Cyamopsis tetragonoloba* (L.) Taub.) genotypes under various irrigation regimes with and without biogenic silica amendment in arid Southwest US. *Plants*, *12*(13), 2486. https://doi.org/10.3390/plants12132486

Gautam, R., Verma, A. K., Dwivedi, S., & Jhang, T. (2024). Breeding guar (*Cyamopsis tetragonoloba* (L.) Taub): A variety compendium of a multifaceted industrial crop for resource-constrained scenario in India. *Industrial Crops and Products*, *214*, 118502. https://doi.org/10.1016/j.indcrop.2023.118502

Ghorbani, M., Ramazani, S. H. R., Fallahi, H. R., & Mousavi Koohi, S. M. (2019). Effect of drought stress and bio-fertilizer on yield and yield components of guar (*Cyamopsis tetragonoloba* (L.) Taub). *Journal of Medicinal Plants and By-products*, *8*(1), 13–19.

Gresta, F., Sortino, O., Santonoceto, C., Issi, L., Formantici, C., & Galante, Y. M. (2013). Effects of sowing times on seed yield, protein and galactomannans content of four varieties of guar (*Cyamopsis tetragonoloba* L.) in a Mediterranean environment. *Industrial Crops and Products*, *41*, 46–52. https://doi.org/10.1016/j.indcrop.2012.04.007

Hussain, M. B., Lucas, J. A., & Maqsood, M. (2021). Biomass nitrogen fixation in legumes: Guar vs soybean comparative study. *Plant and Soil*, *462*, 145–159.

Jamal, Z., Ali, S., Khan, M. A., et al. (2022). Irrigation scheduling and water use efficiency of guar (*Cyamopsis tetragonoloba*) under arid conditions. *Journal of Arid Environments*, *205*, 104812. https://doi.org/10.1016/j.jaridenv.2022.104812

Kaplan, M., Kale, H., Karaman, K., & Unlukara, A. (2017). Influence of different irrigation and Urea levels on crude oil and fatty acid composition of maize (*Zea mays* L.). *Grasas y Aceites*, *68*(3), e207. https://doi.org/10.3989/gya.0222171

Kumar, R., Pareek, N. K., Rathore, V. S., Nangia, V., Kumawat, A., Kumar, A., & Meena, M. (2022). Performance of cluster bean (*Cyamopsis tetragonoloba*) under varying levels of irrigation and urea. *Legume Research*, *47*.1536–1542. https://doi.org/10.18805/LR-4897

Lambers, H., Chapin, F. S., III, & Pons, T. L. (2008). *Plant Physiological Ecology*. 2nd ed. Springer.

Liu, L., Qi, D., Ding, C., Chen, S., Gao, L., & Yue, W. (2025). Optimization of irrigation and urea fertilization improves biomass, yield, and quality of fertigation tomatoes. *Horticulturae*, *11*(5), 521. https://doi.org/10.3390/horticulturae11050521

MarketsandMarkets. (2025). *Guar Gum Market by Application (Food and Beverages, Oil and Gas, Pharmaceuticals), Form, and Region - Global Forecast to 2030*. MarketsandMarkets Research Pvt. Ltd.

Marschner, H. (2012). *Marschner's Mineral Nutrition of Higher Plants*. 3rd ed. Academic Press. 656.

Meftahizade, H., Hamidoghli, Y., Assareh, M. H., & Dakheli, M. J. (2017). Effect of sowing date and irrigation regimes on yield components, protein and galactomannan content of guar (*Cyamopsis tetragonoloba* L.) in Iran climate. *Australian Journal of Crop Science*, *11*(11), 1481–1487. https://doi.org/10.21475/ajcs.17.11.11.pne758

Mudgil, D., Barak, S., & Khatkar, B. S. (2014). Guar gum: Processing, properties and food applications—a review. *Journal of Food Science and Technology*, *51*(3), 409–418. https://doi.org/10.1007/s13197-011-0522-x

Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. (2016). *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. 4th ed. Wiley.

Nejad, N. H., Einali, A., & Ziaei, S. M. (2023). Reduction of drought stress effects on guar (*Cyamopsis tetragonoloba* L.) using ascorbic acid and calcium carbonate. *Legume Res*, *46*(2), 171–175. https://doi.org/10.18805/LRF-709

Paulson, G. D., & Roloff, M. E. (1997). The effect of request form and content on constructing obstacles to compliance. *Communication Research*, *24*(3), 261–290. https://doi.org/10.1177/009365097024003003

Shakir, M., Sadaqat, H. A., Farooq, Q., Shabir, M., Sodagar, A., Nadeem, M., Zafar, T., Ullah, A., Rafiq, F., Anwar, R., Rizwi, A., Amjad, S., & Sajida, A. M. (2020). A review on guar (*Cyamopsis tetragonoloba* L.): A cash crop. *International Research Journal of Pharmacy*, *11*(4), 1–7. https://doi.org/10.7897/2230-8407.110433

Siddiqui, M. H., Alamri, S. A., Al-Khaldi, M. F., et al. (2024). Water requirement and yield response of guar to deficit irrigation strategies. *Agric Water Manag*, *285*, 108345. https://doi.org/10.1016/j.agwat.2024.108345

Singh, J., Angadi, S., Begna, S., VanLeeuwen, D., Idowu, O. J., Singh, P., Trostle, C., Gowda, P., & Brewer, C. (2024). Deficit irrigation strategy to sustain available water resources using guar. *Industrial Crops and Products*, *211*, 118272. https://doi.org/10.1016/j.indcrop.2024.118272

Soltani-Gerdefaramarzi, S., Hoseinollahi, M., Meftahizadeh, H., Bovand, F., & Hatami, M. (2024). Differential responses of two local and commercial guar cultivars for nutrient uptake and yield components under drought and biochar application. *Scientific Reports*, *14*(1), 23–36. https://doi.org/10.1038/s41598-024-74849-9

Sortino, O., & Gresta, F. (2007). Growth and yield performance of five guar cultivars in a Mediterranean environment. *Italian Journal of Agronomy*, *2*(4), 359–364.

Stafford, D. W. (1980). *Kinman guar: A new variety for the Great Plains*. USDA Agricultural Research Service Publication.

Tahmouzi, S., Meftahizadeh, H., Eyshi, S., Mahmoudzadeh, A., Alizadeh, B., Mollakhalili-Meybodi, N., & Hatami, M. (2023). Application of guar (*Cyamopsis tetragonoloba* L.) gum in food technologies: a review of properties and mechanisms of action. *Food Science & Nutrition*, *11*(9), 4869–4897. https://doi.org/10.1002/fsn3.3383

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2015). *Plant Physiology and Development*. 6th ed. Sinauer Associates. 782.

Thapa, S., Adams, C. B., & Trostle, C. (2018). Root nodulation in guar: Effects of soils, Rhizobium inoculants, and guar varieties in a controlled environment. *Industrial Crops and Products*, *120*, 198–202. https://doi.org/10.1016/j.indcrop.2018.04.060

Thombare, N., Jha, U., Mishra, S., & Siddiqui, M. Z. (2016). Guar gum as a promising starting material for diverse applications: a review. *International Journal of Biological Macromolecules*, *88*, 361–372. https://doi.org/10.1016/j.ijbiomac.2016.04.001

USDA. (2025). *World Agricultural Production: Guar Outlook*. United States Department of Agriculture Foreign Agricultural Service. January 2025.

Vishnyakova, M. A., & Buravtseva, T. V., et al. (2023). Genetic diversity and yield potential of guar cultivars under semi-arid conditions. *Euphytica*, *219*, 67.

Vishnyakova, M. A., Frolova, N., & Frolov, A. (2023). Drought stress response in guar (*Cyamopsis tetragonoloba* (L.) Taub): Physiological and molecular genetic aspects. *Plants*, *12*(23), 3955. https://doi.org/10.3390/plants12233955

Zhai, W., Cheng, Q., Duan, F., Huang, X., & Chen, Z. (2025). Remote sensing-based analysis of yield and water-fertilizer use efficiency in winter wheat management. *Agricultural Water Management*, *311*, 109390. https://doi.org/10.1016/j.agwat.2025.109390