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Research article

Effect of fertility levels and stress mitigating chemicals on nutrient content, uptake, intercropping advantage and competition effect in cowpea-baby corn intercropping

Anju Bijarnia [a,*], J.P. Tetarwal [a,***], Rajendra Kumar Yadav [a,**], A.L. Bijrania [b], Deepak Singh [c], Yonika Saini [a]

[a] Agriculture University, Kota, 324001, Rajasthan, India
[b] Agriculture University, Jodhpur, 342304, Rajasthan, India
[c] Division of Sample Surveys, ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India

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ABSTRACT

The primary goal of this study was to analyze how various row ratios of intercrops, in conjunction with different fertilizer levels with spray of two stress mitigating chemical, affect nutrient content, land productivity, and economic viability during *Summer* season. Furthermore, we aimed to explore the competitive dynamics within legume/cereal intercropping systems. Hence, A field experiment at Agriculture University, Kota, during the summers of 2019 and 2020, investigated different cowpea + baby corn intercropping system's intercropping indices, nutrient dynamics, uptake, and post-harvest soil nutrient balance under varying recommended fertilizer levels and foliar spray of stress mitigating chemicals. Using a split-split plot design replicated four times, the experiment involved thirty treatment combinations, including five intercropping techniques *viz.* Sole cowpea, sole baby corn, cowpea + baby corn 2:1, cowpea + baby corn 3:1, cowpea + baby corn 4:1 in the main plot, three fertility levels *viz.* 100 %, 125 % and 150 % recommended dose of fertilizer (RDF) in subplots, and two stress mitigation chemicals; $CaCl_2$ 0.5 % and KNO_3 1% in sub-subplots. The findings revealed notable trends, including nitrogen (N) and (P) content in cowpea seeds and straw, baby corn cobs and fodder, as well as enhanced land-equivalent ratio (LER) and monetary advantage index (MAI) within the cowpea + baby corn 2:1 row ratio. However, despite these advantages, total N and P uptake were markedly higher in sole crops. Notably, sole cowpea demonstrated the highest actual N and P balance and lowest was under sole baby corn. Among the fertility levels, the 150 % RDF level exhibited the most favorable outcomes across various parameters, including LER, MAI, NP content, and uptake in both crops. Additionally, higher fertility levels correlated with increased apparent and actual soil nutrient balances. While, among stress mitigation chemicals, $CaCl_2$ 0.5 % resulted in significantly heightened N and P uptake. Hence, to optimize intercropping dynamics and maintain soil nutrient balance, it is advisable to intensify cowpea cultivation along with baby corn in a 2:1 row ratio, utilizing 150

Abbreviations: IC, intercropping techniques; C_1, sole cowpea; C_2, sole baby corn; C_3, cowpea + baby corn 2:1; C_4, cowpea + baby corn 3:1; C_5, cowpea + baby corn 4:1; F_1, 100 % RDF (Recommended dose of fertilizers); F_2, 125 % RDF; F_3, 150 % RDF; SC, stress mitigation chemicals; S_1, $CaCl_2$ 0.5 %; S_2, KNO_3 1 %; N, Nitrogen; P, phosphorus; LER, land-equivalent ratio; MAI, monetary advantage index; CR, Competition ratio.

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: anjubijarnia95@gmail.com (A. Bijarnia), jptetarwal@gmail.com (J.P. Tetarwal), raj91yadav@gmail.com (R.K. Yadav).

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% RDF is beneficial. Additionally, alleviating higher temperature stress during the summer season can be achieved by applying a 0.5 % solution $CaCl_2$ through spraying at the flowering and pod development stages of cowpea.

1. Introduction

The ecological intensification of agriculture, emphasizes both increasing agricultural production and resource use efficiency in alignment with social and economic contexts [1]. In the face of contemporary agriculture's excessive reliance on inputs, there is an urgent call to reduce this dependency, thereby mitigating greenhouse gas emissions and restoring ecological balance. Alternative agricultural practices, such as intercropping, cover cropping, catch cropping, companion planting, and living mulch systems, emerge as key solutions [2]. These innovative practices not only bolster soil organic carbon content but also enhance aggregate stability, water-holding capacity, and infiltration rates. Notably, these practices contribute significantly to mitigating carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from the soil, marking a significant shift towards sustainability [2]. Intercropping, recognized as a sustainable production strategy with low environmental impact [3], is a fundamental component of this transformative approach. Widely advocated for adoption across diverse climatic regions, intercropping systems are pivotal for sustainable agricultural intensification, especially in the context of ongoing climate change challenges [4]. By enhancing and sustaining crop yields through increased diversity, intercropping systems promote natural ecosystem services, thereby reducing reliance on agrochemical inputs like weedicides, pesticides, and fertilizers [5,6]. This enhanced productivity and sustainability extend to intercrops such as legumes and cereals. Legumes, when intercropped with cereals, demonstrate no adverse effects on cereal crops due to varying root lengths, differing input requirements, and distinct crop phenology. The mutualistic relationship between crops like baby corn and cowpea is particularly notable, driven by factors such as canopy architecture, rooting patterns, and the release of root exudates by legumes, which fulfill the water requirements of maize crops during short dry spells [7–9]. Ensuring precise adjustment of nitrogen and phosphorus application rates is essential to optimize productivity in intercropping systems [10]. Generally, crop nutrient demand has been encountered by native soil nutrients and extraneous nutrient sources such as fertilizers or manures [11]. Hence, along with the declining soil fertility and abrupt change in climatic events have been quoted as the main basis of low crop yields in most parts of India [12]. The fertilizers play a pivotal role in enhancing grain production, optimizing the nitrogen-phosphorus (NP) ratio, and improving water usage efficiency [13,14]. Nitrogen, a crucial input in agricultural systems, contributes significantly to grain quality and overall crop yield [15–18]. While phosphorus is indispensable for plant structural compounds and serves as a catalyst in essential biochemical processes [19,20]. The simultaneous application of nitrogen and phosphorus is imperative for maximizing crop productivity [21–23]. However, current recommendations for NP fertilizer application are predominantly based on sole cropping systems, such as cowpea cultivation in regions like Rajasthan and Haryana, where recommended doses stand at 20 kg of nitrogen and 40 kg of phosphorus [24]. Despite these recommendations, there exists a notable gap in research pertaining to nitrogen and phosphorus fertilizer management in cowpea and baby corn intercropping systems. Addressing this gap is essential for developing tailored fertilizer management strategies that optimize productivity and resource utilization in these intercropping systems.

As we discussed about climate change previously, it is causing prodigious loss, particularly in the reproductive phase of crops. Temperature stress during crop growth plays a crucial role in determining the crop yield [25]. The climate in south-eastern Rajasthan, India, is characterized by hot summers with frequent rainfall events [26]. Stress conditions during the summer season can lead to modifications in plant growth, morphology and root physiology, affecting ion and water uptake [27]. In north-western India, higher temperatures pose several challenges, including reduced growth rates, decreased yields, and detrimental effects on various physiological parameters, making it particularly challenging to cultivate crops during the summer season due to the elevated temperature stress, which results in higher transpiration losses of water [28]. High temperatures accompanied with prolonged dry spells in the summer season during reproductive phase can cause excessive floral abscission leading to poor pod setting as well as seed yield of cowpea, anther dehiscence and male sterility [29,30]. During summer season night temperature at the time of reproductive phase of cowpea in North-West India remains >20 °C in which may adversely affect the flowering and seed setting in cowpea [31]. However, several osmo-protectants can be used to control the damage and protect the crop from climatic anomalies. Reduction in the yield of field crops can be managed by use of foliar bio-regulators, as these can modify plant physiological/biochemical processes during biotic and abiotic stresses [32]. $CaCl_2$ and KNO_3 are osmo-protectants that improve photosynthesis, cell division, cell elongation and influence the crop growth through their effect on water uptake, root growth, maintenance of turgor and transpiration in cells, and activate many enzymes under environmental stress conditions [32].

Recent study has underscored the significance of understanding the spatial dynamics of competitive interactions among intercrops [33]. The land-use advantage of intercropping systems can be quantified using the land equivalent ratio (LER). For example, a study revealed that the wheat/maize relay intercropping system, where maize was planted about 50 days after wheat sowing, showed the greatest land-use advantage [34]. In relay intercropping, each crop species utilizes resources at different times, avoiding direct competition with neighbouring crops. This leads to higher LER values compared to systems where intercrops compete simultaneously for resources, as noted in some studies [35,36]. However, in our study, intercropping involves simultaneous growth of both crops, leading to competition for space. Hence, it's crucial to investigate the land advantage, intra-species competition, and the economic benefits of intercropping. Moreover, research on the spatial dynamics of nutrient uptake, especially N and P, in semi-arid irrigated regions like Rajasthan, is limited. Therefore, understanding how spatial differences affect nutrient content, uptake, and post-harvest balance in intercrops is essential for explaining the reasons behind the high yields and land-use efficiency observed in intercropping systems.

Therefore, this study was initiated to (i) assess the effects of fertility levels and stress mitigating chemical on monetary returns (MAI) in cowpea/baby corn intercropping systems, (ii) determine the influence of the fertility levels and stress mitigating chemicals on nutrient content & uptake (N and P) by intercrops cowpea and baby corn intercropping system, and (iii) quantify the land-use advantage of (LER) over sole systems of cowpea and baby corn, as well as competition (Competition ratio) in different intercropping systems.

2. Materials and methods

2.1. Physiography of study area

A field experiment was conducted during the summer season of 2019 and 2020 at the College of Agriculture, Ummedganj, Agriculture University, Kota. The geographical coordinates of the study site are 25°13′ N latitude and 75°28′ E longitude, with an elevation of 271 m above mean sea level (Fig. 1). This location falls within the Central Plateau and Hills zones of India (VIII) and the Humid South Eastern Plain zone (V) of Rajasthan [37].

2.2. Meteorology of the area of study

Fig. 2 illustrates weather parameters such as temperature, relative humidity, rainfall, evaporation, and rainy days at the experimental site. This information originates from the Class 'B' Meteorological Observatory situated at the Agricultural Research Station, Agriculture University, Kota, Rajasthan, India.

2.3. Initial soil texture, pH, NPK content of the experimental field

The soil in the field experiment exhibited a clay loam texture, notable for its considerable depth and favorable drainage properties, characterized by an average bulk density of 1.26 Mg/m^3. The soil in the experimental plot demonstrated moderate levels of organic carbon, available nitrogen, and phosphorus. Its pH leaned slightly alkaline, and it exhibited a high concentration of potassium. The analytical values are detailed in Table 1.

2.4. Experimental setup and treatment application

In this experiment, a split-split plot design with four replications was employed (Table 2). The main plots featured five distinct intercropping systems cowpea sole, baby corn sole, cowpea + baby corn as 2:1, cowpea + baby corn as 3:1 and cowpea + baby corn as 4:1 row ratio. Within each primary plot, three levels of fertility, specifically 100 %, 125 %, and 150 % RDF, were applied in subplots. To mitigate stress, foliar applications of stress-reducing chemicals, namely 0.5 % $CaCl_2$ and 1.0 % KNO_3, were administered in sub-sub plots during the flowering and pod development stages of the cowpea. It is crucial to emphasize that the comparison exclusively involved comparing the farmers' practice KNO_3 treatment with the new $CaCl_2$ treatment, without the inclusion of a control treatment.

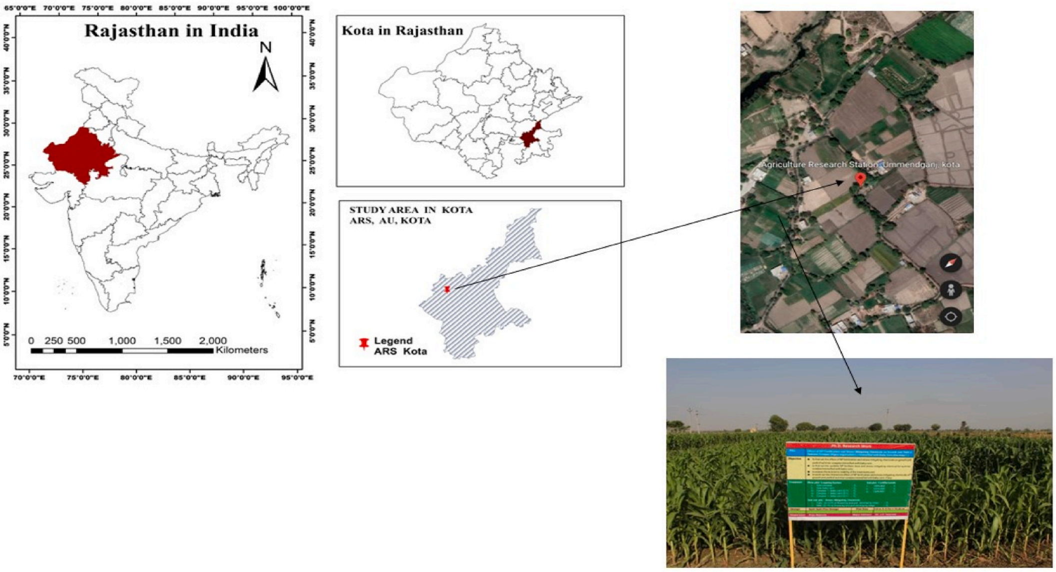

Fig. 1. Location of the experiment conducted at the semi-arid tropics of India (Rajasthan).

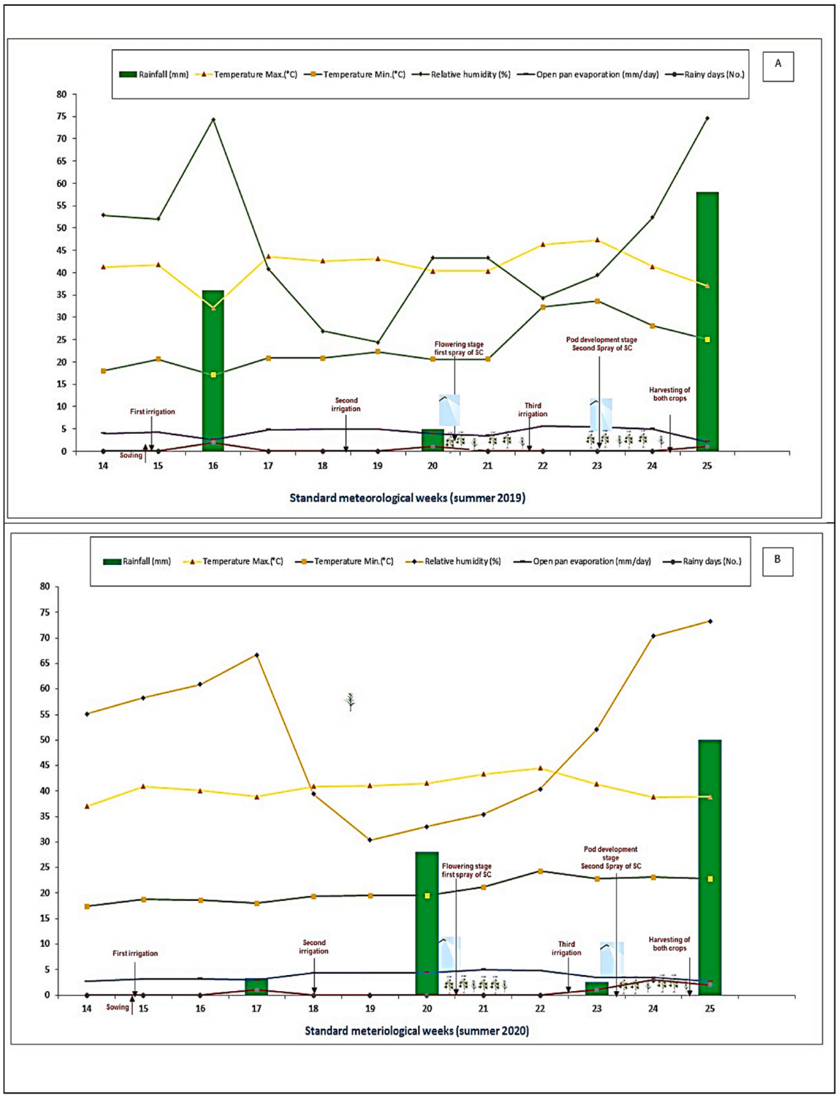

Fig. 2. Meteorological data for the cowpea and baby corn growing season (Summer season) in Kota, India, is provided for the years (A) 2019 and (B) 2020.

For this study, baby corn (variety G 5414) and cowpea (variety GC 4) were selected. To ensure the use of healthy and mature seeds, cowpea and baby corn seeds were simultaneously sown at rates of 30 kg/ha and 25 kg/ha, respectively, based on the specified row arrangements illustrated in Fig. 3. The intercropping system was established using a replacement series approach in the first week of April in both experimental years. Regarding fertilization, the doses were calculated based on three fertility levels: 100 % ($N_{20}P_{40}$), 125 % ($N_{20}P_{50}$), and 150 % of the RDF ($N_{30}P_{60}$). These fertilizer doses were applied before sowing in designated plots using urea and single superphosphate (SSP) in the subplots. To address stress in the cowpea plants, stress-mitigating agents, specifically $CaCl_2$ at a rate of 0.5 % and KNO_3 at a rate of 1 %, were sprayed using a knapsack sprayer in the sub-subplots during the flowering and pod development stages. Throughout the experiment, established guidelines and regulations were followed, and standard protocols were employed for all methodologies.

2.5. Measurements

2.5.1. Assessment of soil nutrients

2.5.1.1. Nutrient content and uptake in cowpea and baby corn. At the harvest stage, representative samples of seeds and straw were collected for the assessment of N and P content. Each dry sample of seeds and straw was ground into a fine powder using a Willey mill to facilitate nutrient content analysis. The estimation of nutrient content in both seeds and straw was conducted in accordance with the

Table 1
Soil properties of experimental field during 2019 & 2020.

	Soil properties	Value obtained	
		2019	2020
A.	**Mechanical**		
	(i) Sand (%)	25.10	26.14
	(ii) Silt (%)	40.12	39.21
	(iii) Clay (%)	34.78	34.65
	(iv) Textural class	Clay loam	Clay loam
B.	**Physical**		
	(i) Bulk density (Mg/m^3)	1.25	1.27
	(ii) Particle density (Mg/m^3)	2.63	2.66
	(iii) Field capacity (%)	51.62	50.67
C.	**Chemical**		
	(i) Organic carbon (%)	0.52	0.50
	(ii) Available N (kg/ha)	311.9	315.3
	(iii) Available P (kg/ha)	24.8	21.3
	(iv) Available K (kg/ha)	397.0	390.2
	(v) (v) ECe of saturated extract at 25 °C (dS/m)	0.36	0.39
	(vi) pH (1:2) soil water suspension	7.59	7.68

Table 2
Description of the experimental set up.

Treatment	Treatment short form	Split-Split plot design 1	Split-Split plot design 2	Split-Split plot design 3	Slit-Split plot design 4
Main plot (Intercropping system)					
(i) Sole cowpea	C_1	C_1	–	C_1	–
(ii) Sole baby corn	C_2	–	C_2	C_2	–
(iii) Cowpea + baby corn (2:1)	C_3	C_3	C_3	C_3	C_3
(iv) Cowpea + baby corn (3:1)	C_4	C_4	C_4	C_4	C_4
(v) Cowpea + baby corn (4:1)	C_5	C_5	C_5	C_5	C_5
Sub plot (Fertility levels)					
(i) 100 % RDF (N_{20} P_{40})	F_1	F_1	F_1	F_1	F_1
(ii) 125 % RDF (N_{25} P_{50})	F_2	F_2	F_2	F_2	F_2
(iii) 150 % RDF (N_{30} P_{60})	F_3	F_3	F_3	F_3	F_3
Sub-sub plot (Stress mitigating chemicals)					
(i) $CaCl_2$ @ 0.5 %	S_1	S_1	S_1	S_1	S_1
(ii) KNO_3 @ 1.0 %	S_2	S_2	S_2	S_2	S_2

procedures described in the following sections on nitrogen and phosphorus content analysis.

2.5.1.2. Nitrogen content. A 0.5-g sample of the material was digested using 10 mL of concentrated sulfuric acid. The determination of total nitrogen (N) was carried out utilizing the Kjeldahl method, following the guidelines specified by Piper in 1966 [37].

2.5.1.3. Phosphorus content. Phosphorus was determined by digesting 0.5 g sample material with triple acid mixture of HNO_3, $HClO_4$ and H_2SO_4 in the ratio of 10:4:1 and developing colour using a portion of the digest following Vanado-molybdate yellow colour method [38]. The intensity of colour was measured using Spectronic 20 spectrophotometer at a wavelength of 470 nm.

2.5.1.4. Nutrient uptake. The percentage of N and P in seed and straw was multiplied by the corresponding dry matter to determine the nutrient uptake of crop, which was expressed as kg/ha [39].

$$\text{Total Uptake (kg / ha)} = \frac{\text{Nutrient content (\%) in seed} \times \text{Seed yield (kg/ha)} + \text{Nutrient content in straw} \times \text{Straw yield (kg/ha)}}{100}$$

2.5.2. Assessments of intercropping indices

2.5.2.1. Land-equivalent ratio. It denotes relative land area under sole crop required to produce the same yield as obtained under mixed or an intercropping system at the same level of management. It was computed by the formula-

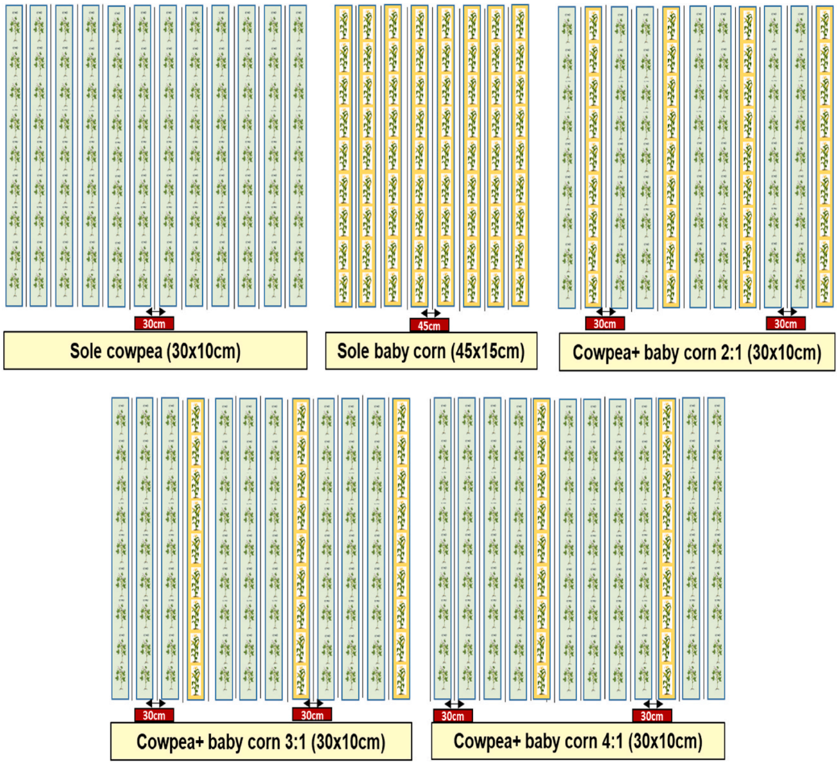

Fig. 3. Experimental plot design illustrating sowing pattern of evaluated two sole crops (sole cowpea & sole baby corn) and three intercropping systems (IS) of cowpea and baby corn.

$$LER = \frac{\mathrm{Yab}}{\mathrm{Yaa}} + \frac{\mathrm{Yba}}{\mathrm{Ybb}}$$

where,

Yaa: Yield of component 'a' in pure stand.

Ybb: Yield of component 'b' in pure stand.

Yab: Yield of component 'a' in mixed stand with 'b'.

Yba: Yield of component 'b' in mixed stand with 'a'.

LER values exceeding 1 signify a yield advantage in intercropping, whereas those below 1 signify a disadvantage. Consequently, it is recommended to cultivate the respective crops independently, or in pure stands, when LER values indicate a disadvantage [40].

2.5.2.2. Monetary advantage index. It is a very common practice of examining intercropping advantage by expressing yields in monetary terms. The calculation of monetary advantages is then almost in variably done by comparing equal sown proportions of intercrops and sole crops. It was calculated according to Willey (1979) [41] as.

MAI was calculated by using the following formula-

$$\mathrm{MAI} = \frac{[\,\text{Value of combined intercrops} \times (\mathrm{LER} - 1)]}{\mathrm{LER}}$$

This calculation assume that the appropriate economic assessment of intercropping should be in terms of increased value per unit area.

2.5.2.3. Competition ratio. It compares the competitive ability of different crops in an intercropping system. Competition ratio is calculated for each component crop separately [42]. Competition ratio of crop *a* on crop *b* is calculated as:

$$\mathrm{CR_a} = \frac{Y_{ab}}{Y_{aa}\ \mathrm{X}\ Z_{ab}} \div \frac{Y_{ba}}{Y_{bb}\ \mathrm{X}\ Z_{ba}}$$

Yab:Yield of component crop a in mixed with b.

Yba:Yield of component crop b in mixed with a.

Yaa:Yield of component crop a in pure stand.

Ybb:Yield of component crop b in pure stand.
Zab: Sown proportion of crop a in mixture with crop b.
Zba: Sown proportion of crop b in mixture with crop a.

2.5.3. Assessment of nutrient budgeting (N & P)

Nutrient budgeting was worked out by preparing a nutrient balance sheet of soil worked out in terms of expected balance, apparent balance and actual balance.

Expected Balance: This was calculated as the difference between the total nutrient added and the nutrient uptake by the crops. Total nutrients added encompassed both indigenous nutrients (initial soil nutrient status) and any additional nutrients applied during the experiment.

Expected Balance = Total nutrient added - Nutrient uptake.

Apparent Balance: The apparent balance was determined as the difference between the soil nutrient status after the experiment and the expected balance.

Apparent Balance = Soil nutrient status after the experiment - expected balance.

Actual Balance: The actual balance was calculated by subtracting the initial soil nutrient status from the soil nutrient status after the experiment. A positive actual balance indicated a net increase in soil nutrient storage, while a negative actual balance indicated nutrient depletion.

Actual Balance = Soil nutrient status after the experiment - Initial soil status.

2.6. Statistical analysis

Utilizing SAS version 9.4, the experimental data were subjected to split-split plot design analysis of variance using various treatments with intercropping system (cowpea sole, baby corn sole, cowpea + baby corn as 2:1, cowpea + baby corn as 3:1, and cowpea + baby corn as 4:1 row ratio) as main factors, Fertility levels [100 % RDF (N_{20} P_{40}), 125 % RDF (N_{25} P_{50}) & 150 % RDF (N_{30} P_{60})] as sub factors and Stress mitigating chemicals ($CaCl_2$ @ 0.5 % & KNO_3 @ 1 %) as sub-sub factors. To distinguish the statistically importance of the differences between the mean values, the Tukey's range test at probability 1 % and 5 % was applied.

3. Results

The study investigated the impact of intercropping, fertility levels, and stress mitigating chemicals on various parameters of cowpea, baby corn as well as intercropping indices. The ANOVA presented in Table 3 provided a comprehensive overview of the significance levels ($P < 0.01$ for significant, $P > 0.01$ for non-significant) of different treatments on the variables studied.

3.1. Nutrient content

Cowpea: In the present study, the N content in both seed and straw of cowpea exhibited significant variations ($p < 0.01$) across different IC methods. Among the diverse IC strategies examined, the implementation of C_3 stood out, demonstrating a remarkable increase in the N content of both seed and straw compared to other IC systems. The nitrogen content in cowpea seed and straw was measured at 3.46 % and 1.64 %, respectively, as depicted in Fig. 4. Similarly, P content was significantly influenced by the various IC systems ($p < 0.01$), with Fig. 5 illustrating the pronounced effects. Notably, among the different IC practices, C_3 emerged as particularly noteworthy, resulting in a significantly elevated level of P in cowpea seeds (0.50 %) and straw (0.24 %). This disparity was statistically significant when compared to the outcomes of C_1, C_2, C_4, and C_5 systems of IC. Regarding fertility levels, the implementation of F_3, as visually depicted in Fig. 4, yielded remarkable results ($p < 0.01$), notably enhancing the N content within both the seeds and straw of summer cowpea. Notably, this increase was most pronounced when contrasted with lower fertility levels, specifically F_1 and F_2. Moreover, the P content in both seeds and straw exhibited a noteworthy response to the F_3 treatment. Significantly higher levels of P were observed, with values reaching 0.44 % and 0.21 % in seeds and straw, respectively, under the F_3 treatment (Fig. 5). In contrast, the data pertaining to the influence of stress mitigating chemicals on the nutrient concentration of cowpea, as depicted in Fig. 4, indicated that the N concentration in both seed and straw of summer cowpea remained statistically unaltered across the various SC treatments. Similarly, when examining P content, the application of SC treatments did not produce any significant effects, as illustrated in Fig. 5.

Baby corn: The ANOVA analysis in Table 3 reveals a significant impact of IC on both N and P content in the cob and fodder of baby corn ($p < 0.01$). Examining the observed and analyzed N content data for cob and fodder of summer baby corn in Fig. 6, it's apparent that among the IC methods, C_3 exhibited higher N content compared to C_2, C_5, and C_4. Conversely, C_2 showed lower N content in both cob and fodder compared to C_5, C_4, and C_3. Analysis of the data in Fig. 7 indicates a significant increase in P content in both cob and fodder of baby corn with all IC ratios compared to sole baby corn cultivation. Particularly, C_3 showed a significant increase in P content over C_2 and other row ratios (C_4, C_5) in both cob and green fodder. The percentage increase in P content in row ratio C_3 was noteworthy, at 37.2 % and 84.7 % over C_2, 22.7 % and 42.1 % over C_5, and 9.4 % and 5.2 % over C_4 in cob and fodder, respectively, averaged over two years. Additionally, C_4 also demonstrated a significant improvement in P content compared to C_2 and C_5. The analysis from Table 3 indicates a statistically significant effect of fertility levels on N and P content in both cob and fodder (p 0.01). It's evident that increasing fertility levels led to a significant increase in N content up to F_3 in cob and fodder of summer baby corn. The highest mean N content was observed at F_3, which was 4.5 % and 2.5 % higher in cob, and 2.5 % and 1.3 % higher in fodder compared

Table 3
Significant levels of effect of intercropping system, fertility levels and stress mitigating chemicals and their interaction on different variables. Note *means significant at 5 %, **highly significant at 1 %.

Source	Mean sum of square																	
	Cowpea							Baby corn						Intercropping indices				
	DF	N content		P Content		N uptake	P uptake	N content		P Content		N uptake	P uptake	DF	CI	MAI	DF	LER
		Seed	Straw	Seed	Straw			Cob	Fodder	Cob	Fodder							
Site	1	0.075*	0.263**	0.0044**	0.00185**	648.5**	13.862**	0.3666**	0.0078**	0.002**	0.0020**	18.9*	1.30*	1	0.021	493968	1	0.0000004
Block(Site)	6	0.008	0.002	0.0002	0.00004	12.4*	0.238	0.0066	0.00052	0.00010	0.00004	3.69	0.53*	6	0.007	7455114	6	0.0204
C	3	3.207**	2.311**	0.1396**	0.03528**	246.5**	3.398**	5.6196**	0.334**	0.198**	0.171**	8044**	457**	2	0.061**	91566162*	4	0.4601**
Site*C	3	0.029	0.079**	0.0002	0.00005	11.2	0.018	0.0600**	0.0008*	0.00007	0.00013	0.36	0.067	2	0.001	14455127	4	0.0023
Block*C(Site)	18	0.009	0.004	0.0002	0.00006	6.9	0.130	0.0047	0.0006**	0.00014	0.00005	1.78	0.464	10	0.009	10360239	24	0.0075
F	2	0.215**	0.052**	0.0054**	0.00141**	586.0**	12.323**	0.1314**	0.0044**	0.009**	0.0089**	145**	26.0**	2	0.009	17993101*	2	0.0344*
Site*F	2	0.001	0.00001	0.000010	0.00002	8.3	0.198	0.00001	0.00004	0.000005	0.000002	0.02	0.005	2	0.014	3788264	2	0.0057
Block*F(Site)	12	0.009	0.0017	0.000171	0.00009	4.3	0.070	0.0052	0.00026	0.00020	0.000013	1.58	0.187	11	0.021	6497015	12	0.0194
F*C	6	0.002	0.0003	0.000038	0.00003	3.0	0.052	0.0004	0.00013	0.00003	0.00012	3.74	1.06**	4	0.011	4745933	8	0.0064
Site*F*C	6	0.001	0.0011	0.000045	0.00001	7.1	0.119	0.0011	0.00002	0.00001	0.000006	0.04	0.003	4	0.007	19187950	8	0.00435
S	1	0.019	0.0081	0.000250	0.00013*	113.8**	2.455**	0.0236	0.00057	0.00006	0.00003	26**	3.0**	1	0.001	7283278	1	0.00737
Site*S	1	0.001	0.0006	0.000016	0.00002	0.3	0.035	0.0003	0.00000	0.00001	0.00002	0.13	0.006	1	0.006	33982	1	0.0029
Block*S(Site)	6	0.012	0.0021	0.0002	0.00001	5.9	0.108	0.0044	0.00024	0.00008	0.00005	1.22	0.173	5	0.015	12192169	6	0.0231
S*C	3	0.012	0.0004	0.0003	0.00001	1.6	0.033	0.0003	0.00002	0.00002	0.00001	3.13	0.380	2	0.003	174267	4	0.00174
S*F	2	0.016	0.0052	0.0002	0.00003	2.5	0.183	0.0034	0.00002	0.00032	0.000006	1.92	0.091	2	0.010	6260324	2	0.0070
S*F*C	6	0.019	0.0055	0.0004	0.00002	7.2	0.107	0.0015	0.00007	0.00005	0.000017	0.77	0.013	4	0.003	28704400	8	0.0038
Site*S*C	3	0.003	0.0004	0.00004	0.00001	0.4	0.002	0.0007	0.00002	0.000001	0.00011	0.04	0.102	2	0.008	6167674	4	0.00067
Site*S*F	2	0.0001	0.0018	0.0001	0.00002	5.0	0.120	0.0006	0.00000	0.000001	0.00028	0.03	0.280	2	0.007	31455921	2	0.00018
Site*S*F*C	6	0.001	0.0011	0.0001	0.00002	1.9	0.034	0.0010	0.00003	0.00001	0.00008	0.02	0.143	1	0.019	1495732	8	0.0004

Note: C; intercropping system, F; fertility levels; S; Stress mitigating chemicals, CI; Competition ratio, MAI; Monetary advantage index, LER; land equivalent ratio.

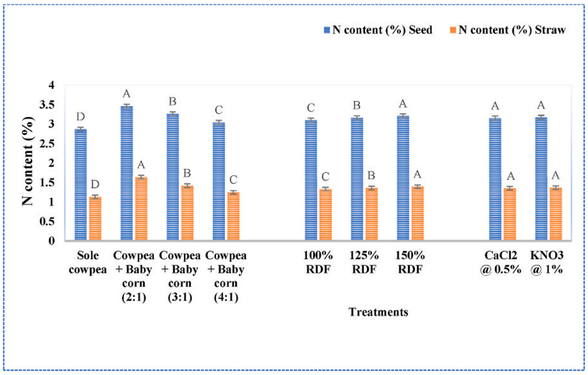

Fig. 4. Nitrogen content (%) of cowpea as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

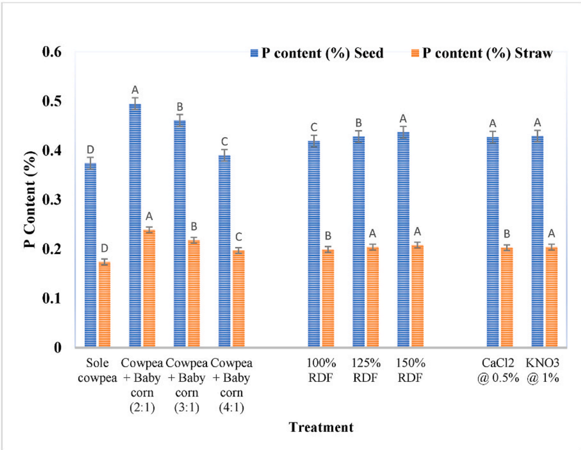

Fig. 5. Phosphorus content (%) of cowpea as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

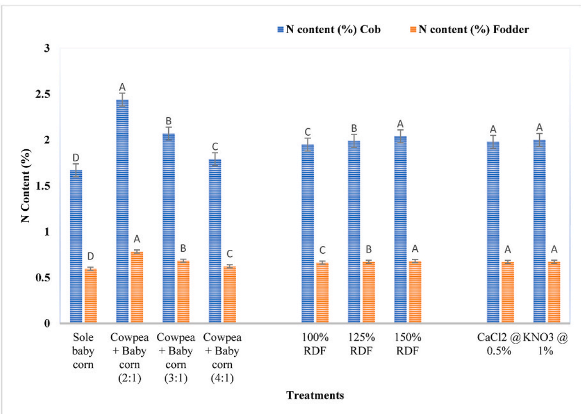

Fig. 6. Nitrogen content (%) of baby corn as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

to F_1 and F_2, respectively (Fig. 6). Analysis of observed and analyzed data for P content in Fig. 7 revealed that the application of fertility level F_3 resulted in significantly higher P content in cob and fodder compared to preceding fertility levels (F_2 & F_1). Furthermore, ANOVA results in Table 3, as well as examination of Figs. 6 and 7, indicated that stress-mitigating chemicals did not bring any significant effect on N & P content in cob or fodder of summer baby corn.

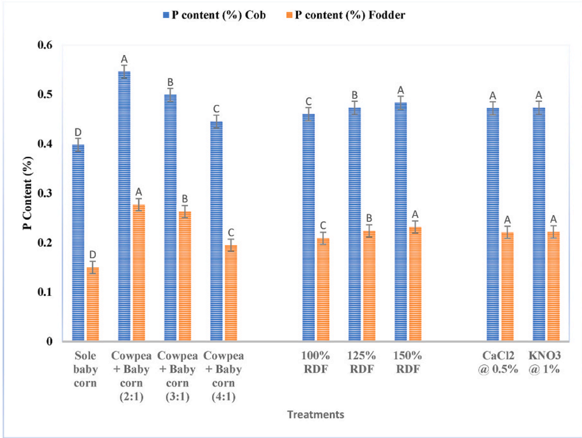

Fig. 7. Phosphorus content (%) of baby corn as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

3.2. Nutrient uptake

Cowpea: Intercropping methods had significant ($p < 0.01$) influence on total N and P uptake by cowpea. Among different IC methods, C_1 in which cowpea was as sole crop exhibited a notably higher total uptake of N and P in comparison to cowpea grown under intercropping systems with row ratios (C_3, C_4, C_5). Interestingly, the intercropping row ratios of C_3, C_4, and C_5 demonstrated similar total N and P uptake patterns, remaining on par with each other (Fig. 8). Further examination of the impact of fertility levels on nutrient uptake revealed a significant enhancement ($p < 0.01$) in the total N & P uptake of summer cowpea with increasing fertility levels, as depicted in Fig. 8. Particularly the highest and most significant increase in N uptake (34.31 kg/ha) observed at F_3. This level of fertilization resulted in a remarkable increase of 21.6 % and 9.2 % in N uptake compared to the 100 % and 125 % RDF levels, respectively. Similarly, total P uptake by summer cowpea followed a similar trend, with the F_3 exhibiting 22.3 % and 9.9 % more P uptake than the lower levels (Fig. 8). Different SC exhibited significant effects ($p < 0.01$) on the total nutrient uptake by cowpea. Fig. 8 highlights that the total N & P uptake by summer cowpea reported a notable increase with the application of S_1 compared S_2. Specifically, S_1 increased the mean N uptake by 5.0 % over S_2. Further analysis of the data in Fig. 8 revealed that S_1 recorded significantly higher P uptake compared to S_2, showing a 5.2 % increase in P uptake over S_2.

Baby corn: IC had significant ($p < 0.01$) influence on total N & P uptake by baby corn. In the context of IC methods (Fig. 9), C_2 stands out, showcasing a significantly higher total N & P uptake compared to the C_3, C_4, and C_5. The analysis in Fig. 9 indicates that different fertility levels had a significant impact ($p < 0.01$) on the N uptake of baby corn. Overall, F_3 emerges as a significant contributor to the enhanced total nitrogen uptake by summer baby corn compared to the F_1 and F_2 treatments. Regarding total P uptake by baby corn, the F_3 fertility level significantly increased total P uptake by summer baby corn over the lower levels (Fig. 9). Different SC demonstrated significant effects ($p < 0.01$) on the total nutrient uptake by baby corn. The recorded data on a pooled basis (Fig. 9) clearly indicated that C_1 resulted in a significantly higher total P uptake compared to C_2 in summer baby corn, with an increase of 3.4 % on a pooled basis.

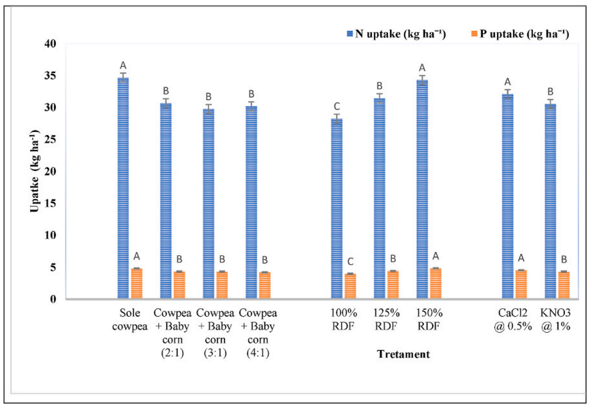

Fig. 8. Nitrogen & phosphorus uptake (kg/ha) of cowpea as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

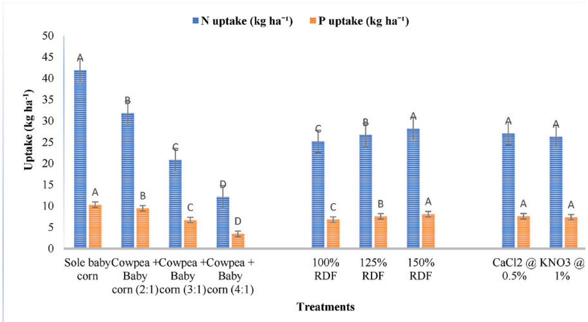

Fig. 9. Nitrogen & phosphorus uptake (kg/ha) of baby corn as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

3.3. Post harvest nutrient budgeting

In Tables 4a–4d, the nutrient budgeting of available N and phosphorus P influenced by intercropping systems is presented. As previously discussed, cowpea and baby corn exhibited the highest uptake of N & P in their respective sole crops. However, considering the total removal by both crops, Table 4b indicates that N removal under C_3 and C_4 treatments was 63 and 51, respectively, while the weighted mean for sole crops averaged 35 and 42 for cowpea and baby corn, respectively (averaged over the years 2019 and 2020). Similarly, phosphorus removal under C_3 and C_4 was higher compared to the sole crops. In our study, we computed various nutrient balances, including the expected, apparent, and actual balances. The actual balance specifically accounts for the remaining portion of nutrients in the soil after the crop harvest. A positive actual balance signifies a net accumulation of nutrients in the soil after the crop harvest, indicating potential soil nutrient enrichment. Conversely, a negative actual balance indicates a depletion of nutrients from the soil, suggesting that the nutrient demands of the crop exceeded the available nutrient supply, leading to a reduction in soil fertility. In our study, we found that the actual balance of N was negative (−29 kg/ha) in C_2 on average. However, it was positive in C_1 as well as in all intercropping row ratios involving cowpea. This indicates that growing the legume cowpea in intercropping had a positive effect on soil N content after harvest. Available P presented a negative apparent balance in all the treatments of IC system. But the actual balance of available P was observed to be positive in all IC treatments, including sole crops. The actual balance of available N was also highest in C_1 (49.45 kg/ha). The actual balance of available P was observed to be positive in all IC treatments, including sole crops. The actual balance of P was maximum (11.44 kg/ha) in C_1 whereas it was minimum (3.91 kg/ha) in C_2.

Effect of fertility levels on nutrient budgeting was also presented in Tables 4a–4d Data observed that progressive increase in levels of fertility up F_3 increased both apparent and actual balance of nitrogen in all treatments of fertility. Available phosphorus presented a negative apparent balance in all the treatments of fertility. But the actual balance of available phosphorus was observed to be positive in all the fertility treatments.

Data depicted in Tables 4a–4d revealed the balance sheet of available N and P influenced by stress mitigating chemicals. The apparent and actual balance of N was highest in the treatment of S_2 (39.81 & 9.36 kg/ha) over S_1. Available P presented a negative apparent balance in both the treatments of SC, while the actual balance of available P was observed to be positive in both treatments of SC.

Table 4a
Effect of intercropping systems, NP fertilization and stress mitigating chemicals on nutrient budgeting (NP) of soil after harvest of cowpea and baby corn.

Treatment	Soil contribution						Addition					
	N (kg/ha)			P (kg/ha)			N (kg/ha)			P (kg/ha)		
	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean
A. Intercropping system												
Sole cowpea	312	319	316	25	27	26	25	25	25	50	50	50
Sole baby corn	312	319	316	25	27	26	25	25	25	50	50	50
Cowpea + Baby corn (2:1)	312	319	316	25	27	26	25	25	25	50	50	50
Cowpea + Baby corn (3:1)	312	319	316	25	27	26	25	25	25	50	50	50
Cowpea + Baby corn (4:1)	312	319	316	25	27	26	25	25	25	50	50	50
B. Fertility level												
100 % RDF (N_{20} P_{40})	312	319	316	25	27	26	20	20	20	40	40	40
125 % RDF (N_{25} P_{50})	312	319	316	25	27	26	25	25	25	50	50	50
150 % RDF (N_{30} P_{60})	312	319	316	25	27	26	30	30	30	60	60	60
C. Stress mitigating chemical												
$CaCl_2$ @ 0.5 %	312	319	316	25	27	26	25	25	25	50	50	50
KNO_3 @ 1 %	312	319	316	25	27	26	25	25	25	50	50	50

Table 4b
Effect of intercropping systems, NP fertilization and stress mitigating chemicals on nutrient budgeting (NP) of soil after harvest of cowpea and baby corn.

Treatment	Total						Removal					
	N (kg/ha)			P (kg/ha)			N (kg/ha)			P (kg/ha)		
	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean
A. Intercropping system												
Sole cowpea	337	344	341	75	77	76	33	36	35	4.6	5.1	4.8
Sole baby corn	337	344	341	75	77	76	42	42	42	10	10	10
Cowpea + Baby corn (2:1)	337	344	341	75	77	76	61	64	63	14	14	14
Cowpea + Baby corn (3:1)	337	344	341	75	77	76	49	53	51	11	11	11
Cowpea + Baby corn (4:1)	337	344	341	75	77	76	42	43	42	7.5	7.9	7.7
B. Fertility level												
100 % RDF (N_{20} P_{40})	332	339	336	65	67	66	42	44	43	8.5	8.8	8.6
125 % RDF (N_{25} P_{50})	337	344	341	75	77	76	45	48	47	9.5	9.7	9.6
150 % RDF (N_{30} P_{60})	342	349	346	85	87	86	48	52	50	10	10	10.
C. Stress mitigating chemical												
$CaCl_2$ @ 0.5 %	337	344	341	75	77	76	46	49	47	9.6	9.9	9.7
KNO_3 @ 1 %	337	344	341	75	77	76	44	47	46	9.2	9.5	9.4

Table 4c
Effect of intercropping systems, NP fertilization and stress mitigating chemicals on nutrient budgeting (NP) of soil after harvest of cowpea and baby corn.

Treatment	Soil status (NP) after experiment						Expected balance					
	N (kg/ha)			P (kg/ha)			N (kg/ha)			P (kg/ha)		
	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean
A. Intercropping system												
Sole cowpea	362	368	365	37	38	37	304	308	306	70	72	71
Sole baby corn	282	290	286	28	32	30	295	303	299	64	67	66
Cowpea + Baby corn (2:1)	325	332	329	32	33	33	276	280	278	61	63	62
Cowpea + Baby corn (3:1)	334	341	337	33	35	34	288	291	290	64	66	65
Cowpea + Baby corn (4:1)	344	353	348	35	38	36	295	301	298	67	69	68
B. Fertility level												
100 % RDF (N_{20} P_{40})	315	324	320	28	30	29	290	295	293	56	59	57
125 % RDF (N_{25} P_{50})	331	337	334	33	35	34	291	296	294	65	68	66
150 % RDF (N_{30} P_{60})	342	349	345	38	40	39	293	298	296	75	77	76
C. Stress mitigating chemical												
$CaCl_2$ @ 0.5 %	327	335	331	32	34	33	291	296	293	65	67	66
KNO_3 @ 1.0 %	331	338	335	34	36	35	293	297	295	66	68	67

Table 4d
Effect of intercropping systems, NP fertilization and stress mitigating chemicals on nutrient budgeting (NP) of soil after harvest of cowpea and baby corn.

Treatment	Apparent balance						Actual balance					
	N (kg/ha)			P (kg/ha)			N (kg/ha)			P (kg/ha)		
	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean
A. Intercropping system												
Sole cowpea	58	61	59	−34	−34	−34	50	49	49	12	11	11
Sole baby corn	−12	−13	−13	−36	−36	−36	−30	−29	−29	3.7	4.2	3.9
Cowpea + Baby corn (2:1)	49	53	51	−29	−30	−30	13	13	13	7.0	6.0	6.5
Cowpea + Baby corn (3:1)	45	50	47	−31	−31	−31	22	22	22	8.3	8.1	8.2
Cowpea + Baby corn (4:1)	49	52	50	−32	−32	−32	33	33	33	10	11	10
B. Fertility level												
100 % RDF (N_{20} P_{40})	25	29	27	−28	−28	−28	3.5	5.2	4.3	3.3	3.1	3.2
125 % RDF (N_{25} P_{50})	40	41	40	−32	−32	−32	19	18	19	8.2	7.9	8.1
150 % RDF (N_{30} P_{60})	48	51	50	−37	−37	−37	30	30	30	13	13	13
C. Stress mitigating chemical												
$CaCl_2$ @ 0.5 %	37	40	38	−34	−33	−33	15	16	16	6.9	6.7	6.8
KNO_3 @ 1 %	39	41	40	−31	−31	−31	19	19	19	9.6	9.1	9.4

3.4. Contribution of nutrient content and removal in intercropping advantage and competition effect

Different IC methods significantly ($p < 0.01$) influenced the LER values of cowpea and baby corn intercropping. The LER of the cowpea-baby corn intercropping system decreased with decreasing rows of baby corn (Fig. 11). The LER values in C_3 (1.23), C_4 (1.14), and C_5 (1.07) treatments were greater than 1, showing the advantages in the intercropping system. The advantage of intercropping was mainly due to the increase in nutrient removal (Table 4b). Over a two-year period, the C_3 system demonstrated the highest average LER, followed by C_4 and C_5. Consequently, C_3 displayed superior biological efficiency compared to C_4 and C_5, as evidenced by substantially higher LER (Fig. 10), peaking at 1.23. The heightened biological efficiency carries significant economic implications for intercropping systems, as reflected in MAI. Fig. 11 unequivocally illustrates that C_2 enhances the overall MAI compared to C_4 and C_5. The highest MAI (8855) was obtained by the C_3 system, followed by C_4 (Rs. 5201) and C_5 (Rs. 2629).

Moreover, the competition ratio serves as a valuable metric for assessing competitive dynamics between crops and was significantly ($p < 0.01$) affected by different IC systems, as indicated in the ANOVA of Table 3. A lower CR value for cowpea suggests lower competitiveness relative to baby corn (Fig. 12). A CR value for cowpea falling below one indicates a positive benefit of cowpea on baby corn, suggesting profitable co-cultivation. Notably, under C_5, cowpea exhibited a higher CR value compared to C_3 and C_4, signifying more intense interspecific competition faced by cowpea.

Furthermore, the study revealed from Table 3 that fertility levels significantly affected LER and MAI ($p < 0.05$). Data from Fig. 10 indicate that the application of F_3 fertility level significantly increased the LER of the cowpea and baby corn intercropping system over F_1 and F_2 during the mean analysis of two years. Similarly, data from Fig. 11 showed that fertility levels F_3 also increased the MAI over lower fertility levels. However, the CR value was not significantly affected by any fertility level.

Nevertheless, SC did not exhibit a significant effect on the LER, MAI and CI in cowpea and baby corn intercropping system.

4. Discussion

4.1. Nutrient content and uptake

Our experiment demonstrated that intercropping enhanced nitrogen and phosphorus content in both cowpea and baby corn compared to sole cropping. This elevation in nutrient levels was particularly evident in the seed and straw of cowpea, as well as the cob and fodder of baby corn. Several interconnected factors contribute to this improved nutrient profile in intercropping systems. The complementary root architectures of cowpea and baby corn facilitate more efficient nutrient exploration and acquisition. Cowpea, a legume, typically develops a shallower root system, while baby corn roots penetrate deeper soil layers. This spatial complementarity in root distribution enhances overall nutrient uptake efficiency, a phenomenon also observed in maize-faba bean intercropping systems [43]. The inclusion of legumes in intercropping systems augments soil nitrogen availability through biological nitrogen fixation. The fixed nitrogen can be transferred to the non-legume crop (baby corn) via various pathways, including root exudation, decomposition of nodules and roots, and direct transfer through mycorrhizal networks [44]. This nitrogen transfer likely contributed to the elevated nitrogen content observed in baby corn under intercropping conditions. Additionally, intercropping stimulates enhanced rhizosphere interactions. The diverse root exudates released by both crops intensify microbial activity in the rhizosphere, leading to increased nutrient mineralization and availability [45]. This "rhizosphere priming effect" results in improved nutrient content for both intercropped species, a finding corroborated by additional studies [33,46].

Despite the increase in nutrient content, the total uptake of nitrogen and phosphorus by individual crops was higher in their respective sole cropping systems. This apparent contradiction stems from the reduced plant population and decreased yield of each crop in intercropping (Supplementary 1-2), as nutrient uptake is a function of both concentration in plant tissues and overall yield. Similar findings have been reported in other studies [43]. Interestingly, when considering the combined removal of nitrogen and phosphorus in intercropping scenarios, particularly those with higher baby corn populations, we observed greater overall nutrient removal. The C_3 treatment, which had a higher proportion of baby corn, demonstrated the highest nutrient removal, with a progressive increase noted as the baby corn population increased (Table 4b). This suggests that intercropping may offer advantages in total nutrient utilization when both crops are considered collectively.

The enhanced total nutrient removal in intercropping systems, especially with higher baby corn populations, can be attributed to several factors. Complementary resource use plays a significant role, as the differing resource acquisition strategies of shallow-rooted cowpea and deep-rooted baby corn lead to more efficient exploitation of soil nutrients [47]. Temporal nutrient demand differences also contribute, as cowpea and baby corn likely have distinct peak nutrient demand periods, allowing for more efficient nutrient utilization over time [48]. Facilitative interactions further enhance nutrient availability, with the presence of cowpea potentially improving phosphorus availability for baby corn through rhizosphere acidification and the release of organic acids [43]. Additionally, intercropping systems often yield higher total biomass compared to sole cropping due to more efficient resource use, leading to higher overall nutrient removal, even if individual crop yields are reduced [49].

The underlying biological mechanism driving the crop yield advantage in terms of nutrition is predominantly attributed to the augmentation of nutrient removal. This systemic nutrient advantage arises not only from escalated nutrient removal but also from enhanced nutrient transfer and utilization efficiency [50]. Additionally, interspecies competition for soil and fertilizer nitrogen in intercropping can enhance the ability of weakly competitive legumes to fix atmospheric nitrogen [51]. In the C_3 row ratio, where the baby corn population increased, interspecies competition intensified. Baby corn demonstrated a greater capacity to compete for nitrogen compared to cowpea alone in the intercropping system. This competitive dynamic can be explained by several factors. Root architecture differences play a crucial role, as baby corn typically develops a more extensive and deeper root system than cowpea,

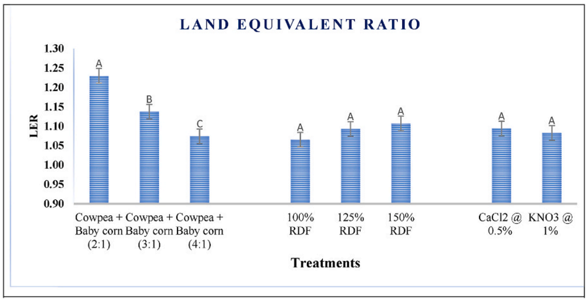

Fig. 10. Land equivalent ratio as affected by different intercropping systems, fertility levels and stress mitigating chemicals.

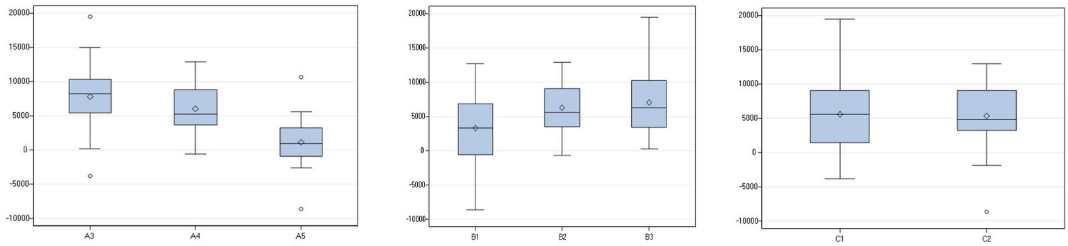

Fig. 11. Monetary advantage index as affected by different intercropping systems, fertility levels and stress mitigating chemicals. A3; cowpea + baby corn (2:1), A4; cowpea + baby corn (3:1), A5; cowpea + baby corn (4:1), B1; 100 % RDF, B2; 125 % RDF, B3; 150 % RDF, C1; $CaCl_2$ 0.5 %, C2; KNO_3 1 %.

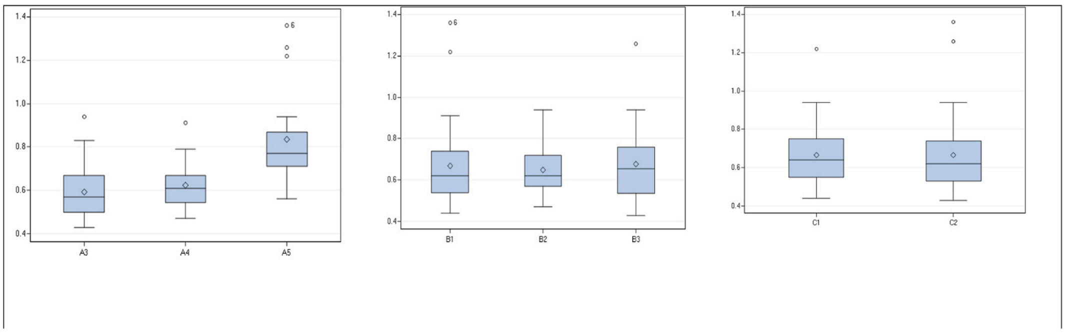

Fig. 12. Competition ratio of cowpea as affected by different intercropping systems, fertility levels and stress mitigating chemicals. A3; cowpea + baby corn (2:1), A4; cowpea + baby corn (3:1), A5; cowpea + baby corn (4:1), B1; 100 % RDF, B2; 125 % RDF, B3; 150 % RDF, C1; $CaCl_2$ 0.5 %, C2; KNO_3 1 %.

allowing it to access a larger soil volume and compete more effectively for nutrients [52]. Physiological differences also contribute, as baby corn, being a C4 plant, has a higher nitrogen requirement compared to the C3 legume cowpea, driving more aggressive nitrogen acquisition [53]. Furthermore, growth rate differences impact nutrient acquisition, with baby corn often exhibiting more rapid early-season growth compared to cowpea, leading to a competitive advantage in nutrient uptake during critical early growth stages [54].

The enhanced nitrogen absorption by intercropped baby corn leads to a reduction in soil nitrogen levels within the cowpea root zone compared to sole cowpea cultivation (Table 4c). This nitrogen deficiency stimulates the nitrogen fixation capacity of legume crops, resulting in a substantial increase in nitrogen removal throughout the system [51]. This phenomenon, known as the "N sparing effect," has been observed in various legume-cereal intercropping systems and contributes to the overall nitrogen use efficiency of the system [55]. Furthermore, nitrogen fixed by legumes in legume/non-legume intercropping systems can be transferred to and utilized by non-legume crops [56], potentially contributing to increased nitrogen removal in intercropping. Similar findings have been reported in studies of rye–pea [57], maize–peanut [58], and maize-soybean [51] intercropping systems.

Regarding phosphorus dynamics, both crops showed significantly higher phosphorus removal (Table 4b) in C_3 and C_4 treatments compared to sole crops. The C_3 treatment, in particular, exhibited superior phosphorus removal compared to C_1, C_2, C_4, and C_5 treatments. This enhanced phosphorus removal in intercropping systems can be attributed to several mechanisms. Rhizosphere acidification plays a role, as legumes like cowpea can acidify their rhizosphere through proton release during nitrogen fixation, increasing phosphorus solubility and availability, particularly in calcareous soils [45]. Root exudates also contribute, as both cowpea and baby corn release organic acids and phosphatases into the rhizosphere, mobilizing otherwise unavailable forms of phosphorus. The diversity of root exudates in intercropping systems may lead to more efficient phosphorus solubilization compared to sole cropping [43]. Mycorrhizal networks are another important factor, as intercropping can promote the development of more extensive mycorrhizal networks, facilitating phosphorus transfer between intercropped species and potentially leading to improved overall phosphorus uptake [59]. Additionally, complementary phosphorus acquisition strategies come into play, with cowpea and baby corn employing different approaches such as cluster root formation in cowpea and increased root hair density in baby corn, resulting in more efficient exploitation of soil phosphorus reserves [48]. The pivotal role of roots in controlling phosphorus uptake and enhancing faba-maize cropping system productivity has been emphasized in previous studies [60]. Additionally, canopy cover emerges as a critical factor in regulating nutrient uptake and enhancing productivity in intercropping systems [61,62]. In our study, the narrower spacing within baby corn plants, particularly in the C_3 treatment (2:1 row ratio), led to increased canopy cover compared to other ratios in the cowpea crop. This expanded canopy cover effectively reduced solar radiation reaching the soil surface, consequently moderating soil temperature [63]. A recent study found that incorporating baby corn into a cowpea crop as an intercrop can significantly reduce the canopy temperature by up to 7 °C compared to sole cowpea cultivation, particularly during the summer season [26]. Moreover, the increased canopy cover likely facilitated N and P solubilization while reducing their loss [62]. Consequently, this condition likely contributed to heightened total nutrient removal in the cowpea and baby corn intercropping system, thereby bolstering the yield of this system (Supplementary 3). Similar results were also observed in a study of a maize-soybean intercropping system [51].

The application of 150 % RDF significantly enhanced both nitrogen and phosphorus content in the seeds and straw of summer cowpea, alongside an increased total uptake of these nutrients. This improvement is linked to better nutrient translocation and absorption, reflecting a more favorable nutritional environment in the rhizosphere and plant tissues. Several mechanisms explain why higher fertility levels lead to increased nutrient content and uptake. Increased nutrient availability stimulates root proliferation, enhancing the plant's ability to intercept and absorb nutrients, as observed in crops like maize and wheat [64]. Enhanced root growth is a key factor, where higher nutrient availability promotes root development, leading to better nutrient interception and uptake. Additionally, increased nutrient supply boosts the expression and activity of nutrient transporters in plant roots, with nitrogen transporters such as NRT1 and NRT2 showing upregulation under higher nitrogen conditions [65]. Synergistic effects also play a role, where the balanced application of nitrogen N and P enhances nutrient uptake. Phosphorus availability can improve nitrogen uptake by promoting root growth and increasing the energy available for active nutrient transport [66]. Moreover, higher nutrient levels can alter rhizosphere pH and microbial activity, potentially increasing nutrient solubility and availability [45]. Nutrient uptake is influenced by both the concentration of nutrients in the plant and the crop's yield (seed and straw). The observed increases in these attributes with higher fertility levels are likely due to the enhanced fertilization with nitrogen and phosphorus. Increased nitrate reductase activity, which plays a crucial role in nitrogen assimilation, may also contribute to improved nitrogen content. This enzyme's activity is often enhanced under higher nitrogen availability [67]. Similar findings have been reported in other studies [68,69&46]].

Conversely, the concentration of N and P in the cob and fodder of baby corn, as well as their total uptake, was significantly higher with 150 % RDF. This increase is likely due to enhanced nutrient translocation facilitated by a more favorable nutritional environment in the rhizosphere and plant system. Several factors contribute to this improved nutrient uptake at higher fertility levels. Firstly, higher nutrient availability promotes root proliferation and branching, increasing the root surface area available for nutrient absorption [69]. Improved nitrogen nutrition also enhances photosynthetic capacity, leading to increased chlorophyll content and photosynthetic efficiency, which supports greater nutrient uptake and assimilation [70]. Additionally, at elevated fertility levels, plants may engage in luxury consumption, storing excess nutrients in vacuoles or other tissues. This can result in higher nutrient concentrations [71]. Moreover, increased nutrient availability can boost the expression of genes involved in nutrient uptake, assimilation, and remobilization, leading to more efficient nutrient utilization across the plant [72]. The positive influence of applied nutrients in enhancing nutrient uptake is evident from the significantly lower nutrient uptake observed in the 100 % RDF treatment, which was lower when supplemented with chemical fertilizers, as reported in earlier studies [73] in baby corn and [74] in maize.

The application of a 0.5 % $CaCl_2$ spray significantly enhanced nitrogen and phosphorus uptake in both summer cowpea and baby corn compared to a 1.0 % KNO_3 spray. This improvement is attributed to the increased seed and straw yield in cowpea and the cob and fodder yield in baby corn associated with the $CaCl_2$ treatment. Several mechanisms explain the superior performance of $CaCl_2$ in enhancing nutrient uptake. Calcium ions contribute to osmotic adjustment, helping plants maintain cell turgor under stress conditions, which improves water relations and nutrient uptake [75]. Additionally, calcium is crucial for membrane stability, as it maintains cell membrane integrity and function. By stabilizing membranes, $CaCl_2$ enhances the selectivity of ion uptake and improves nutrient absorption efficiency [76]. Calcium also acts as a secondary messenger in plant signaling pathways, and $CaCl_2$ application may trigger signaling cascades that boost nutrient uptake and assimilation [77]. Moreover, calcium ions play a role in stomatal regulation, improving water use efficiency and indirectly enhancing nutrient uptake [78]. $CaCl_2$ also effectively mitigates higher temperature stress during the summer season by reducing canopy temperatures. This temperature moderation leads to several benefits for nutrient uptake: it maintains enzyme activity necessary for nutrient uptake and assimilation, such as nitrate reductase and phosphatases [79]; supports healthy root metabolism crucial for active nutrient uptake processes [80]; and enhances nutrient mobility in the soil solution by increasing diffusion rates, making nutrients more accessible to plant roots [81]. Specifically, the 0.5 % $CaCl_2$ treatment resulted in improved relative water content in both cowpea and baby corn, translating into increased yields for both crops. This increase in productivity facilitated greater nutrient uptake, consistent with findings reported in other studies [82].

4.2. Intercropping indices

The advantages of intercropping systems primarily stem from the combined effects of nutrient uptake, utilization, and interactions between crops [51]. This study highlights three key aspects of nutrient content and removal in cowpea and baby corn intercropping. Firstly, the content and removal of nitrogen and phosphorus in the intercropping of cowpea and baby corn, exhibited a positive correlation with the intercropping advantage (LER, MAI). This advantage can be attributed to the complementary resource use between the two crops. Cowpea, as a legume, can fix atmospheric nitrogen, which benefits the non-legume baby corn through nitrogen transfer [44]. Additionally, the differing rooting patterns of cowpea and baby corn enable more efficient nutrient exploration at various soil depths [83]. The increased nutrient removal in intercropping systems compared to sole cropping is due to several factors: enhanced root activity stimulating root growth and exudation [84]; facilitative interactions where one crop may enhance the nutrient uptake of the other through mechanisms such as rhizosphere acidification or enzyme production [85]; and temporal complementarity where different growth rates and nutrient demand peaks allow for more efficient nutrient use over time [47]. A decrease in nutrient content and removal with fewer baby corn rows suggests that the optimal balance of competition and facilitation was achieved at a 2:1 row ratio [86].

Secondly, the LER for C_3, C_4, and C_5 treatments exceeded 1, indicating that the cowpea-baby corn intercropping system is advantageous. This is largely due to the addition of more baby corn rows, which enhances the temporal and spatial complementarity between the two crops, leading to more efficient resource use [48]. The higher LER values with increased baby corn rows suggest that baby corn utilizes resources more efficiently when intercropped with cowpea. This efficiency may be due to the C_4 photosynthetic pathway of baby corn, which generally exhibits higher nutrient use efficiency than C_3 plants like cowpea [87]; its taller stature and extensive root system accessing resources less available to cowpea [52]; and the benefits from nitrogen fixed by cowpea, which are more pronounced with more baby corn plants [88].

Thirdly, the competition ratio showed that baby corn was more competitive than cowpea. This indicates that intercropping resulted in greater land-use efficiency, as baby corn demonstrated superior nutrient competition [40]. The higher competitiveness of baby corn is attributed to its faster growth rate, taller canopy, and more extensive root system compared to cowpea [89]. In intercropping systems, particularly with a 4:1 row ratio, intensified competition arises from the rapid initial growth of baby corn, leading to competition for essential resources like moisture, nutrients, and space throughout the crop cycle. This competitive dynamic is driven by differential growth rates, where baby corn's faster initial growth allows it to dominate early [90]; light interception, where its taller stature may shade cowpea, reducing cowpea's photosynthetic capacity [91]; root distribution, where baby corn's deeper roots access more soil volume [92]; and nutrient demand, with baby corn's higher nutrient needs leading to more aggressive uptake [93].

Furthermore, the application of 150 % RDF recorded significantly higher LER and MAI compared to 100 % and 125 % RDF levels. This superiority is attributed to the comparatively higher yields of both crops at the 150 % RDF level. The incremental increase in RDF levels positively influenced the net returns, with the lower associated costs contributing to a more favorable economic outcome. Similar observations were reported in other studies at different localities of India [94,95].

4.3. Nutrient budgeting

The nutrient balance sheet generated after harvesting the cowpea and baby corn revealed several important findings:

- In the intercropping system involving cowpea, a legume crop, the actual nitrogen balance was positive across all row ratios. This benefit arises from the legume's ability to fix atmospheric nitrogen through its symbiotic relationship with rhizobia bacteria [96]. The biological nitrogen fixation not only supplies nitrogen to the legume itself but also provides advantages to the non-legume crop, such as baby corn, through several mechanisms. First, nitrogen fixed by cowpea can be directly transferred to baby corn via mycorrhizal networks or root exudates [97]. Second, after harvest, the decomposition of cowpea residues releases fixed nitrogen into the soil, which can benefit subsequent crops [98]. Finally, by fixing its own nitrogen, cowpea reduces competition for soil nitrogen, thus leaving more available nitrogen for baby corn [99].
- Negative nitrogen balance in sole baby corn: Conversely, in sole baby corn cultivation, where legumes are not present, the actual nitrogen balance tends to be negative. This situation arises primarily due to the high nitrogen demand of corn coupled with the absence of biological nitrogen fixation, which means there is no additional nitrogen supplied to the soil through legume activity [100].
- Phosphorus balance: The significant improvement in soil phosphorus balance can be linked to the release of hydrogen ions (H^+) by legumes during the process of nitrogen fixation. This acidification of the rhizosphere likely enhances the mobilization of insoluble phosphorus in the soil [84]. Additionally, legumes secrete organic acids and phosphatase enzymes, which can further increase phosphorus availability [101].
- Effect of fertility levels: The data revealed that gradually increasing fertility levels up to 150 % RDF enhanced the actual balance of the cropping system. Positive actual balances of nitrogen (29.90 kg/ha) and phosphorus (13.03 kg/ha) can be attributed to the relatively lower removal of these nutrients compared to their addition to the soil (Table 4d). This may also be due to the increased availability of nutrients in the soil with higher application rates [102].
- Impact of stress mitigating chemicals: The impact of stress mitigating chemicals showed that the apparent and actual balance of nitrogen was highest in the treatment of 1.0 % KNO_3 (39.81 and 9.36 kg/ha) compared to 0.5 % $CaCl_2$. This could be attributed to the higher supply of nitrogen from KNO_3, which increases the available nitrogen in the soil [103]. Available phosphorus exhibited a negative apparent balance in both treatments of stress mitigating chemicals. However, the actual balance of available phosphorus

was positive in both treatments, possibly due to enhanced phosphorus mobilization or reduced phosphorus fixation in the soil [104].

These findings highlight the complex nutrient dynamics in intercropping systems and underscore the importance of considering both crop interactions and management practices in optimizing nutrient use efficiency and soil fertility.

5. Conclusion

In conclusion, our study underscores the substantial advantages of employing a 2:1 row ratio intercropping system of cowpea and baby corn. This configuration not only boosts nutrient content and removal from the soil but also maximizes land utilization effectively. Incorporating cowpea, a legume crop, proves advantageous for soil nutrition health (higher actual balance), while the competitive nature of baby corn further amplifies the intercropping advantage. Adjusting the fertilizer schedule, particularly by increasing the recommended dose of cowpea by 1.5 times, enhances nutrient uptake, soil health, and overall intercropping benefits. Additionally, our findings suggest that mitigating higher temperature stress during the summer season through $CaCl_2$ 0.5 % spray at flowering and pod development stages of cowpea significantly increases yield. Overall, our results underscore the potential of this intercropping system not only from a nutritional and agronomic perspective but also monetary, making it a promising strategy for sustainable agriculture.

CRediT authorship contribution statement

Anju Bijarnia: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **J.P. Tetarwal:** Writing – review & editing, Resources, Conceptualization. **Rajendra Kumar Yadav:** Writing – review & editing, Methodology. **A.L. Bijrania:** Writing – review & editing, Validation, Formal analysis. **Deepak Singh:** Writing – review & editing, Software, Formal analysis, Data curation. **Yonika Saini:** Writing – original draft, Data curation.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e38194.

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