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Influence of plant spacing and deblossoming on agromorphological and physiological traits of zombi pea

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Zombi pea is an underexploited legume vegetable with edible tubers and pods and a climate resilient crop. It carries genes that make it resilient to biotic and abiotic stressors, and have high protein content. Despite its immense potential, zombi pea remains underutilized owing to lack of breeding efforts, less information on agronomic practices, and low awareness among researchers and farmers. Hence, the current study was prudently conducted to elucidate the dynamics of growth, yield, and physiology of zombi pea under variable spacings and deblossoming conditions. The experiment was conducted in split-plot design with three replications comprising a total of 8 sets of treatment combinations. The treatments included 4 variable spacings (S1: 45 cm × 15 cm, S2: 45 cm × 30 cm, S3: 60 cm × 15 cm, S4: 60 cm × 30 cm) with or without deblossoming. Data revealed that the morphological traits such as leaf and stem weight, height of plant, tuber numbers per plant (2.6), tuber weight (322.39 g), length of tubers (16.17 cm), tuber diameter (16.08 cm), and tuber yield/plant (121.85 g) were significantly affected by wider spacing (S4). The results show that the highest values for RGR (relative growth rate) and NAR (net assimilation rate) were recorded at the 45 × 30 cm spacing (S2), but LAI (leaf area index) was highest at the 60 × 30 cm spacing (S4).. The close spacing (S1) is significantly ideal to get the highest total green pod yield (3.46 q/ha), total tuber yield (150.85 q/ha), and improvement in crop growth parameters. The present investigation opens the door to improve the potential of zombi pea by manipulating agronomic and reproductive practices, which in turn will enhance the food and nutritional security.

Keywords Zombi pea, Morpho-physiology, Yield, Deblossoming, Spacing, Food security

The cumulative effect of global population explosion and decreasing crop productivity in face of climate change, present a significant challenge to feed billions[1,2]. The problem of food security is attributed to climatic factors i.e. global warming, post-harvest losses, countries economic status, and not paying much attention to potential minor crops[1,3]. The study of growth, physiology and yield components of neglected and minor crops with inherent potential would pave the way for solving the issues of feeding empty stomachs[4–6]. Hence, it is imperative to invest in research and development of underutilized crops. One of such wonder crops with tremendous potential to tackle the threats of food and nutritional security, is Zombi pea [*Vigna vexillata* (L.) A. Rich] belonging to the family Fabaceae under the genus *Vigna*[7]. There are nine domesticated species under the genus *Vigna,* besides numerous potential wild species that are having value as food and nutritional-feed, green manure and cover crops[8]. Zombi pea [*Vigna vexillata* (L.) A. Rich], a pan tropical crop with wide distribution in the African, Asian, Australian, and American continents, is also addressed by other vernacular names like tuber cowpea[5]. The primary centre of diversity of this orphan crop is South Africa, while the secondary centre of diversity is Southeast Asian region[5,9]. Zombi pea is also widely distributed in peninsular India's hilly-subhilly tracts and in the protected areas of Himalayan regions[10]. In India, Marathi people call it Halunda, in Assam it is known as

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Banoria Urahi, in Bengali it is addressed as Latchai, and the Sanskrit name of zombi pea is Mudgaparni[10]. This wonder crop has edible young shoots, tubers, and green tender seeds[11–13]. The herbage of this orphan crop is utilized as fodder, and it is also valued as a cover crop[14]. This crop is also valued as a pulse crop in the form of dry seeds[15], besides having a therapeutic and medicinal value of various plant parts[16]. Despite having a wide array of multipurpose applications and benefits, little breeding and genetics efforts have been devoted to explore the genetic potential of this underutilized wonder crops[7,10]. Zombi pea has a close association with cowpea [*Vigna unguiculata* (L.) Walp.] as the genome of zombi pea is conserved with cowpea genome and both are potential food, protein, fodder and cover crops[17,18]. The zombi pea is a home of protein enrichment genes and contains about 15% of protein content which is three times higher than the staple tuber crops such as potato and yam[5]. As compared to other commercial tuber crops like cassava, the protein content of zombi pea is about six folds higher[19].

Zombi pea is a climate smart tuberous legume and carries genes for resistance to biotic stresses (e.g., bruchid resistance) and abiotic stresses (salinity, waterlogged conditions, alkaline soils, drought, etc.)[5,13,20–22]. The roots of zombi pea are fusiform and are consumed in raw form or after boiling in the tribal hilly regions of India[23]. The fusiform zombi pea roots have better nutrition and flavour than sweet potato[24]. The wide range of variability exists in the hilly tracks of North-East India including eastern and western Ghats[25,26]. Seed types and tuber types are two domesticated forms of zombie pea occur in Sudan (Africa) and the Indonesian region, respectively[5,19,27,28]. This wonder crop can perform better during the rainy season and have the ability to tolerate the waterlogged conditions for a period of six months. It has the quick growing habit and covers the soil area rapidly[11–13].

The crop plant yield is highly influenced by plant density, which mostly depends on plant spacing. The crop yield is also altered by the competition within and outside the plant environment, and higher yield is obtained with less competition for edaphic and climatic factors[29]. The optimum plant density and agronomic practices are followed with the objective of improving light interception, photosynthesis, plant architecture, and productivity[30]. The high plant density interferes with proper light interception by plant canopy[30], which results in an increase in leaf senescence, a reduction in photosynthesis rate, and eventually low yield. The behaviour of different genotypes towards plant spacing is variable due to variation in plant growth and development phenomena among them[31]. Ezedinma[32] reported high biological and grain yield of cowpea when plants were grown at closer spacing, which could be explained by accommodation of a greater number of plants per unit area in close spacing. The narrow plant spacing offers a competitive advantage over weeds and reduces the growth of weeds[33]. In addition to this, the rapid canopy development at close spacing causes higher interception of light per unit leaf area index (LAI), which increases the rate of photosynthesis, and better growth and development are obtained[34].

The flowers are the primary plant organs which play a significant role in the accumulation, translocation and transport of sugar and dry matter, which ultimately alters the quality of produce and endogenous hormone levels[35–37]. The carbohydrate distribution to tubers is influenced by flower removal, and high tuber yield is achieved[38]. Likewise, improvements in tuberization have been observed in other tuberous legume crops in response to the removal of pods[39]. Optimizing the crop management practices is crucial to unlock the crop genetic potential. Keeping in view the potential of Zombi pea as a climate smart crop for addressing the issues of food and nutritional security, it was selected as a choice crop to be investigated. It was hypothesized that understanding the interplay of plant spacing and deblossoming can provide valuable insights into optimizing zombi pea production systems. The lack of information on the effects of plant spacing, plant population, and deblossoming on improving plant growth indicators, physiology, and yield components of *Vigna vexillata* per se in India, promulgated us to undertake the current investigation. Thus, during the climate crisis and realizing the potential of this wonder tuberous legume *Vigna vexillata*, the current research was prudently executed to elucidate the impact of variable spacings and deblossoming treatments on improving growth indicators, physiology and yield attributes of zombi pea.

Materials and methods

Study site and plant materials

The experiment was conducted at the research farm of the regional center of ICAR-CTCRI located at eastern coastal plains of Bhubaneswar, Odisha, during the cropping season of 2021–2022. All the field works done at ICAR-CTCRI, Regional Centre only. An indigenous collection of zombi pea 'IC259504' was used in the present investigation. This indigenous collection 'IC259504' was provided by ICAR- CTCRI, Regional Centre, Bhubaneswar[7] for the present investigation. This accession is conserved in the nation seed gene bank of ICAR-NBPGR, New Delhi, India, and was initially collected from Goa state, of India[10]. This line is having indeterminate growth habit and is a cultivated type of *Vigna vexillata*[7]. The detailed information regarding this accession can be found in Tripathi et al.[10]. The soil pH at the study site was 5.63 with an EC of -0.26 and organic carbon content of 0.61%. The prevailing weather conditions during the whole course of the crop life cycle are depicted in the Fig. 1, 2 and 3.

Experimental design, layout and treatments

The present investigation was conducted in a split plot design carrying main plot and sub plot factors. The experiment was conducted consisting of eight sets of treatments and three replications. The treatments in the main plot comprised of 4 variable spacings, viz. 45 cm × 15 cm (S1), 45 cm × 30 cm (S2), 60 cm × 15 cm (S3) and 60 cm × 30 cm (S4). These spacings treatments (S1 to S4) were selected to represent a gradient from dense plant density to wider plant arrangements, allowing the evaluation of plant density effects on crop growth and development. Further, the zombi pea is closely related to cowpea and related beans like mungbean, hence the spacing treatments were selected based upon agronomic recommendations for these legumes. The sub-plot treatments included deblossoming (F1) and F2 (flower retention) treatments. The plan of layout was as per

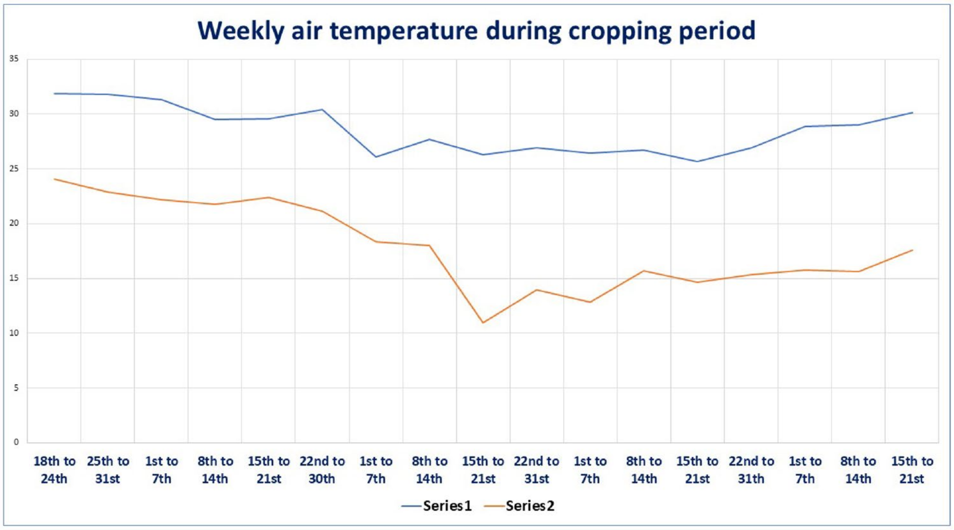

Fig. 1. Weekly weather data, minimum and maximum air temperature during the cropping period at the study location i.e. research farm of ICAR-CTCRI, regional centre, Bhubaneswar, Odisha.

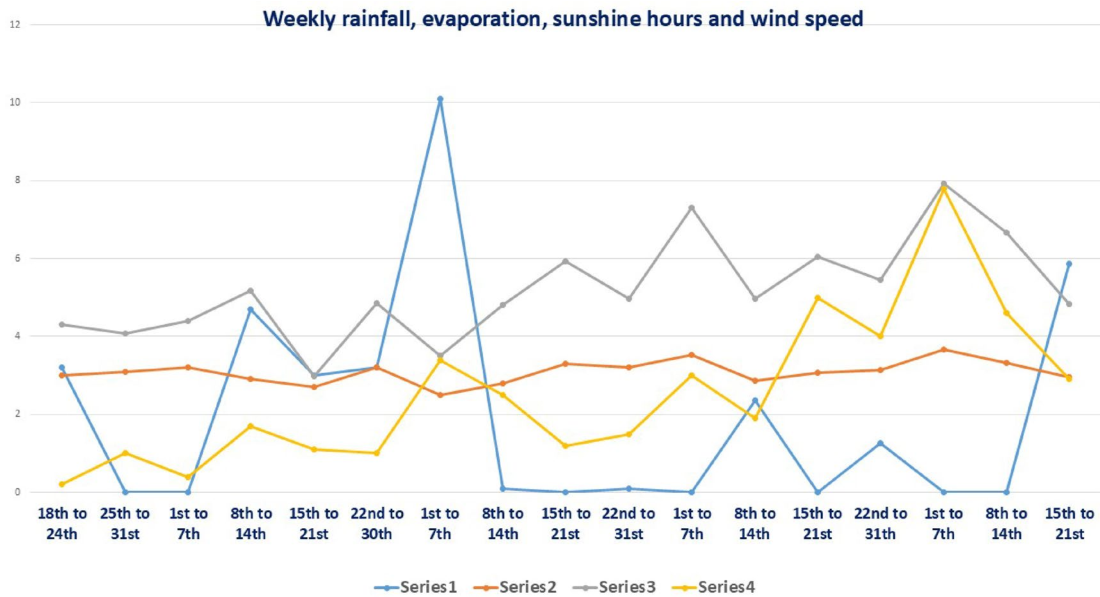

Fig. 2. Weekly weather data representing rainfall, evaporation, sunshine hours and wind speed during the cropping period at the study location i.e. research farm of ICAR-CTCRI, regional centre, Bhubaneswar, Odisha.

Priyadarsini et al.[7]. For the deblossoming (F1) condition, all the flowers were pinched off manually beginning from 60 DAS (days after sowing of seeds) till the peak flowering stage.

Plant growth analysis parameters

For data recording on various traits, 5 plants were selected randomly per plot, excluding the border plants. These selected plants were tagged, and observations were recorded for different growth and physiological, vegetative, agronomic, and yield-related traits. The observations on the height of the plant (cm), girth of the plant (cm), numbers of branches on each plant, leaf numbers per plant, tuber numbers per plant, and per plant tuber yield (g) were recorded from 5 tagged plants. Further, the 5 plants were uprooted per plot to record the data on plant fresh weight (g), plant dry weight (g), leaf area per plant (LA) (cm^2) and leaf area index (LAI). Growth assessment was carried out in terms of leaf area and LAI. The leaf area meter was used to note the leaf area (LA) per plant (cm^2), and leaf area index (LAI) was estimated as total leaf area of a plant/ground area occupied by the plant[40]. Other physiological parameters like leaf area ratio (LAR), leaf area duration (LAD), net assimilation rate

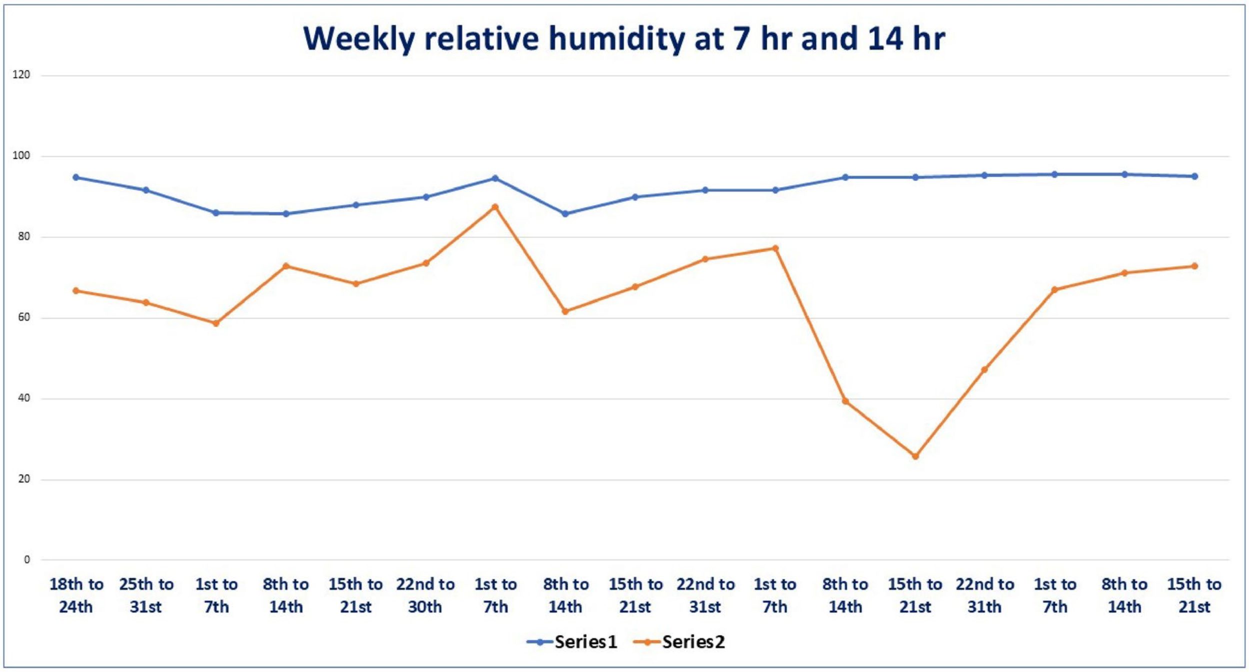

Fig. 3. Weekly status of relative humidity during the cropping period at the study location i.e. research farm of ICAR-CTCRI, regional centre, Bhubaneswar, Odisha.

(NAR), relative growth rate (RGR) and crop growth rate (CGR) were measured as per stated by El-Hendawy et al.[41]. LAR was estimated as leaf area per plant/plant dry weight and LAD was calculated by using the formula L1 + L2/2 × (t2 – t1) where, L1 is LAI at the first stage and L2 is LAI at the second stage. t2 – t1 is time interval in days. The absolute growth rate (AGR) was computed as h2 – h1/t2 – t1, where h2 and h1 are the plant height at t2 and t1 times respectively. The estimation of NAR was carried out as (W2 – W1)/(t2 – t1) × (loge L2 – loge L1)/(L2 – L1) where, W1 and W2 are dry weights of whole plant at time t1 and t2 respectively. The formula loge W2 – loge W1/t2 – t1was used to compute the RGR, where, W1 and W2 are whole plant dry weight at time t1 and t2 respectively. Finally, the CGR was computed by the formula, (W2 – W1)/ ρ(t2 – t1) where W1 and W2 are whole plant dry weights at time t1 and t2 respectively. ρ is the ground area on which W1 and W2 are recorded.

Pod and tuber yield related parameters

The influence of plant population and deblossoming was estimated on pod yield and related traits as well. The observations were recorded on mean weight of pods (g), average length of pods (cm), pod yield per plot (g), nodulation of root, tuber girth (cm), length of tuber (cm), tuber fresh weight (g), dry weight of tuber (g), and tuber yield per plot (g). In each plot, 5 plants were tagged randomly to record the data on pod and tuber yield parameters by excluding the border plants. These selected plants were tagged, and observations were recorded for different pod and tuber traits in zombi pea.

Economic analyses

The economic analysis and further estimation of the benefit: cost ratio are two key indicators for the success of the research programme. The economic analysis was performed as per the CIMMYT[42] according to the prevailing market prices. To estimate the total gross return, the tuber and green pod yields/ha of each treatment were multiplied by the respective sale prices. To estimate the net returns the cost of cultivation of each treatment was subtracted from the respective gross return. To estimate the benefit–cost ratio (B:C ratio), the following formula was used: gross return/total cost of cultivation of each treatment.

Statistical analyses

The statistical software, by following the methodology of Panse and Sukhatme[43] was adopted for data analysis in SPD (split plot design). The significance of statistical analysis of data was tested at a 5% level of significance. The interaction analysis among different traits and treatment combinations was estimated using R programming 'corrplot' package software version 4.1.0 which was utilized to compute the association between variable plant spacings and traits under study.

Ethical approval

The present experiment does not contain any studies with human participants. The present investigation comprising plant studies was performed in accordance with relevant institutional, national, and international guidelines and legislation.

Results

Zombi pea plant phenotype as influenced by variable spacings and deblossoming

The plant height in zombi pea at different intervals is influenced by variable spacings (Table 1, Fig. 4). At 30 days after sowing, the zombi pea attained the maximum plant height (12.96 cm) under wider spacing (S4: 60 cm × 30 cm), which was significantly better than close spacing. Likewise, at wider spacing of 60 cm × 30 cm, zombi pea attained the maximum plant height at different growth stages of 60 days after sowing, 90 days after sowing, and 120 days after sowing. The widest spacing and minimum number of plants per plot in the S4 treatment might have enabled each plant to uptake more nitrogen and other nutrients from the soil owing to less competition, thereby resulting in more vigorous and taller plants. In the initial stage of 30 days after sowing, no significant variation was recorded in plant height under F1 (deblossoming) and F2 (retention of flower) conditions. Then, no significant variation was depicted in the height of zombi pea plants at 30, 60, 90 and 120 days after sowing in all the cases of interaction effects.

In the later stages of 60, 90 and 120 days after sowing, the maximum plant height was observed in the blossom removal (F1) condition as compared to the blossom retention (F2) condition. Deblossoming (F1) definitely arrested the reproductive growth and encouraged more vegetative growth, leading to the taller plant height. The highest plant girth (3.31 cm), number of branches per plant (13.72), and number of leaves per plant were observed in the deblossoming (F1) condition which was significantly better than the blossom retention (F2) condition. All the cases of interaction effects did not depict significant difference with respect to plant girth and number of leaves per plant (Fig. 5). The highest leaf area per plant (545.95 cm^2) was recorded in the wider spacing (S4: 60 cm × 30 cm) which was significantly better than other spacing variables. Similarly, under deblossoming (F1) condition, the highest leaf area per plant (592.62 cm^2) was observed, and it was significantly better than blossom retention (F2) stage. Interaction effects did not exhibit any significant difference in the leaf area of zombi pea. The highest leaf area index (LAI) (0.758) was observed in the wider spacing (S4: 60 cm × 30 cm) and was a significantly better than other spacing variables. In the same fashion, the deblossoming condition (F1) exhibited significantly highest LAI (0.573) than blossom retention (F2) condition. LAI were found to be statistically similar among all the interaction treatments. Highest fresh weight (49.90 g) and dry weight (18.49 g) of leaf and stem were observed in wider spacing (S_4: 60 cm × 30 cm) which were significantly better than closer spacing. Likewise, under deblossoming condition (F1), the maximum fresh weight (49.91 g) and dry weight

Treatment	Plant height (cm) at 30 DAS	Plant height (cm) at 60 DAS	Plant height (cm) at 90 DAS	Plant height (cm) at 120 DAS	Plant girth (cm)	Branches per plant	Leaves per plant	Leaf area per plant (sq. cm.)	Leaf area index	Fresh weight(g) of leaf and stem	Dry weight(g) of leaf and stem
Main plot (Spacing)											
S_1(45 cm x15cm)	6.38	20.05	53.66	59.37	2.85	12.20	10.33	500.533	0.273	38.45	16.40
S_2(45 cm x 30 cm)	6.83	25.86	61.69	68.22	2.97	12.63	10.47	514.533	0.602	44.30	17.71
S_3(60 cm x 15 cm)	6.41	23.80	54.65	64.21	2.88	12.40	10.33	510.050	0.372	39.66	16.86
S_4(60 cm x 30 cm)	12.96	28.25	66.74	69.03	2.54	13.10	11.13	545.950	0.758	49.90	18.49
SE(m) ±	0.506	1.139	2.488	0.753	0.138	0.429	0.762	8.638	0.019	1.264	0.829
CV (%)	36.91	14.50	9.93	6.56	7.12	3.10	3.64	3.78	42.92	11.64	5.16
C.D. at 5%	1.784	4.017	8.776	2.655	NS	NS	NS	30.472	0.068	4.459	NS
Sub plot (Deblossoming)											
F_1(Deblossoming)	8.66	27.57	67.50	72.45	3.31	13.72	11.81	592.617	0.573	49.91	19.33
F_2(Blossom retention)	7.63	21.41	50.87	57.96	2.30	11.46	9.32	442.917	0.429	36.24	15.40
SE(m) ±	0.330	1.062	2.128	1.683	0.050	0.202	0.268	16.324	0.015	1.360	0.645
CV (%)	8.94	17.78	19.88	15.75	25.50	12.69	16.65	20.43	20.40	22.43	16.01
C.D. at 5%	NS	3.517	7.049	5.573	0.166	0.669	0.888	54.061	0.050	4.503	2.137
Interactions											
S_1F_1	6.49	23.77	58.55	65.16	3.40	12.53	11.26	559.833	0.307	49.06	19.64
S_1F_2	6.28	16.33	48.76	53.58	2.30	11.87	9.40	441.233	0.240	27.84	13.16
S_2F_1	7.11	28.11	69.67	74.13	3.43	13.73	11.80	581.333	0.690	47.56	19.12
S_2F_2	6.55	23.61	53.71	62.30	2.50	11.53	9.13	447.733	0.513	41.04	16.29
S_3F_1	7.11	28.05	61.89	74.03	3.47	14.07	11.53	603.367	0.440	48.22	18.73
S_3F_2	5.71	19.55	47.40	54.40	2.28	10.73	9.13	416.733	0.303	31.10	14.98
S_4F_1	13.94	30.33	79.87	76.49	2.95	14.53	12.66	625.933	0.857	54.80	19.82
S_4F_2	11.99	26.16	53.60	61.57	2.13	11.67	9.60	465.967	0.660	44.99	17.16
SE(m) ±	0.7015	1.748	3.711	1.78	0.175	0.565	1.928	18.432	0.028	2.044	1.202
CV (%)	34.07	20.27	18.61	12.40	17.06	9.87	11.75	14.34	41.91	20.07	13.00
C.D. at 5%	NS	NS	NS	NS	NS	1.592	NS	NS	NS	NS	NS

Table 1. Effect of spacing and deblossoming on phenotypic traits of zombi pea.

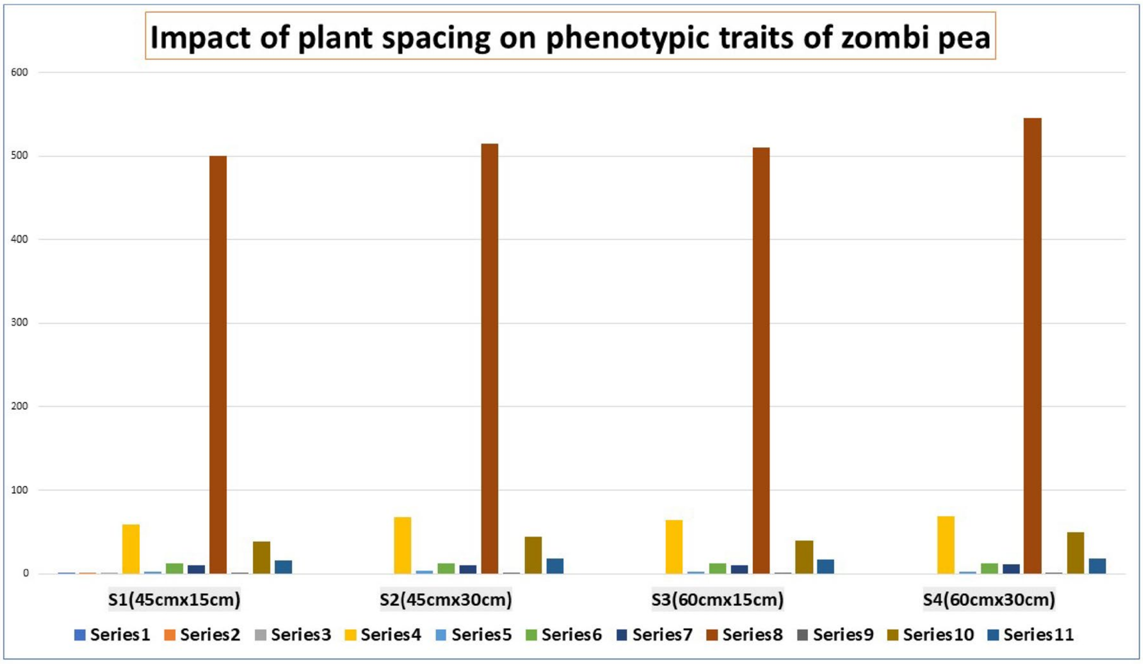

Fig. 4. Impact of plant spacing on zombi pea plant phenotype. Series 1 to 11 with different colour shades denotes 11 different plant phenotypic traits. (Series 1 to series 4: denotes plant height at 30, 60, 90 and 120 days after sowing, respectively. Series 5: plant girth, Series 6: branches/plant, Series 7: leaves per plant, Series 8: leaf area per plant, Series 9: leaf area index, Series 10: fresh weight of leaf and stem, Series 11: dry weight of leaf and stem).

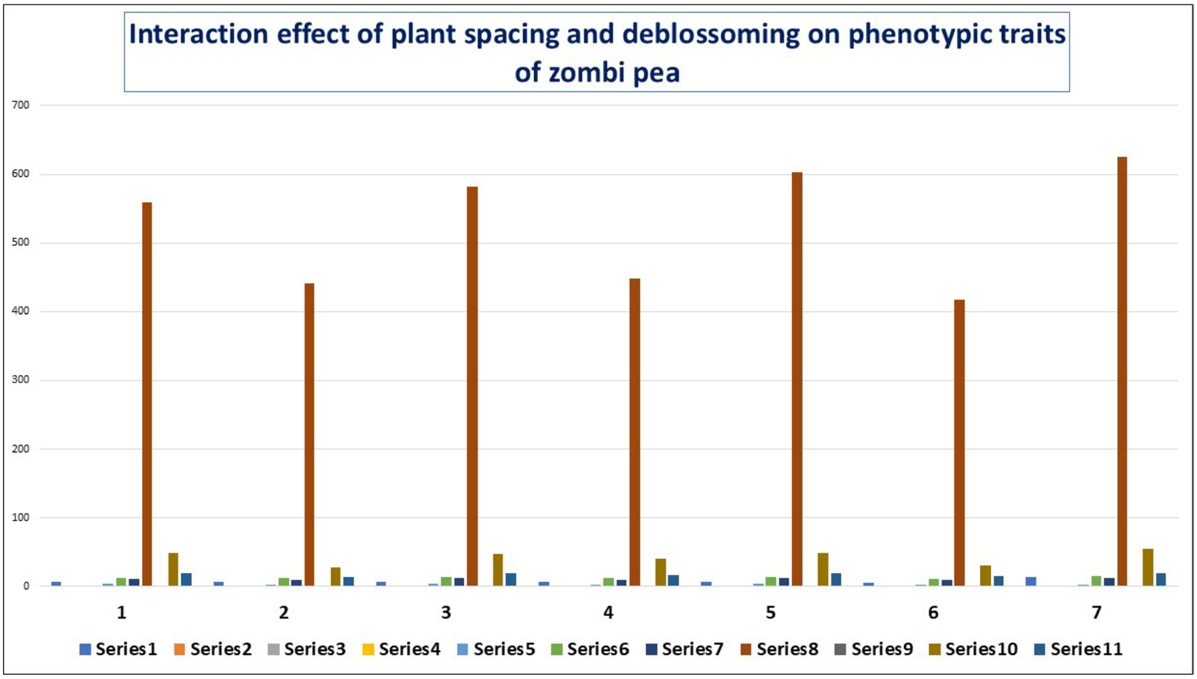

Fig. 5. Interaction effects of plant spacing and deblossoming on zombi pea plant phenotypic traits. Series 1 to 11 with different colour shades denotes 11 different plant phenotypic traits. (Series 1 to series 4: denotes plant height at 30, 60, 90 and 120 days after sowing, respectively. Series 5: plant girth, Series 6: branches/plant, Series 7: leaves per plant, Series 8: leaf area per plant, Series 9: leaf area index, Series 10: fresh weight of leaf and stem, Series 11: dry weight of leaf and stem).

(19.33 g) of leaf and stem was observed which was significantly better than blossom retention (F2) condition (Table 1).

Physiological indicators

The effects of spacing and deblossoming on physiological attributes were variable. The results pertaining to physiological indicators are presented in Fig. 6 (Supplementary Table S1). The findings of the current study indicated that the highest leaf area ratio (LAR) was recorded in a plant spacing of 45 × 30 cm, when flowers were retained on the plants (S2F2 condition). Broadly, it is observed that with the increase in spacing leaf area was increased. The plant grown at close spacing exhibited the highest leaf area duration (LAD) (S1F1) (46.46). The maximum AGR (cm day^{-1}) was recorded at the spacing of 45 × 30 cm under deblossoming conditions. The maximum NAR was recorded at the closest spacing of 45 × 30 cm. The maximum RGR and CGR were recorded at the closest spacing in the flower persistence condition.

In the plant growth and development studies. the sigmoid curve analysis with growth models is used to determine plant growth parameters like leaf area and plant height. In the current study, height of zombi pea plants was measured at four different intervals and followed the sigmoid growth curve (Fig. 7) at different treatments of spacing and deblossoming.

Dynamics of tuber yield under variable plant spacing and deblossoming

Data analysis revealed the significant influence of plant spacing and deblossoming on tuber yield and related traits (Table 2, Figs. 8 and 9). The results revealed that wider spacing (60 cm × 30 cm) prompted the highest tuber girth (16.08 cm). The tuber length was found to be significantly better in the deblossoming (F1) (16.07 cm) condition than in the blossom retention (F2) (13.20 cm) condition. The tuber length, tuber girth was found to be maximum in deblossoming (F1) condition than blossom retention (F2) condition. The interaction effects revealed no significant difference among all the tuber and related traits except for tuber dry weight. The wider spacing also contributed to more numbers of tubers per plant as compared to close spacing (Table 2). Likewise, under deblossoming conditions (F1), the tuber numbers per plant (2.47) were significantly more than the flower retention condition (F2). The highest yield per plant (121.85 g) was observed in large spacing of 60 cm × 30 cm (S4) instead of close spacing. Likewise, the yield of tubers per plant (129.94 g) was significantly higher in the blossom removal (F1) condition than in blossom retention (F2) condition. The highest tuber yield per hectare (150.85 q/ha) was recorded at the S1 treatment which depicts a close spacing of 45 cm × 15 cm, which was significantly better than the wider spacing. The wider spacing of 60 cm × 30 cm (S4) contributed in the highest fresh weight of tuber (322.39 g) than at closer spacings. The widest spacing and a smaller number of plants per plot in S4 (60 cm × 30 cm) condition might have enabled each plant to uptake more nitrogen and other nutrients from the soil, thereby resulting in a high value of tuber fresh weight. Likewise, tuber fresh weight (363.02 g) was highest in deblossoming condition (F1), which was significantly better than blossom retention (F2) condition. The tuber dry weight was not influenced by different spacing treatments. However, the dry weight of tuber (124.55 g) was highest in the blossom removal (F1) condition, which was significantly better than the blossom retention (F2) condition. The highest tuber dry weight was depicted in closer spacing (45 cm × 30 cm) with blossom removal (S2F1), which was significantly better than the other treatment effects. (Table.2).

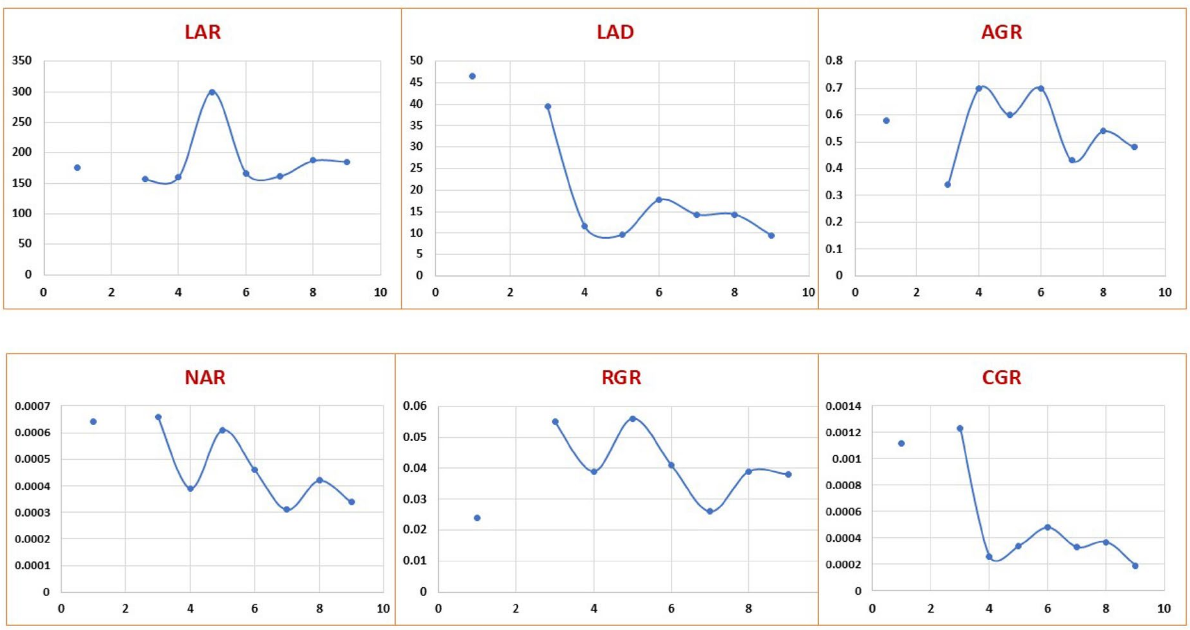

Fig. 6. Influence of plant spacing and deblossoming interaction on physiology of zombi pea.

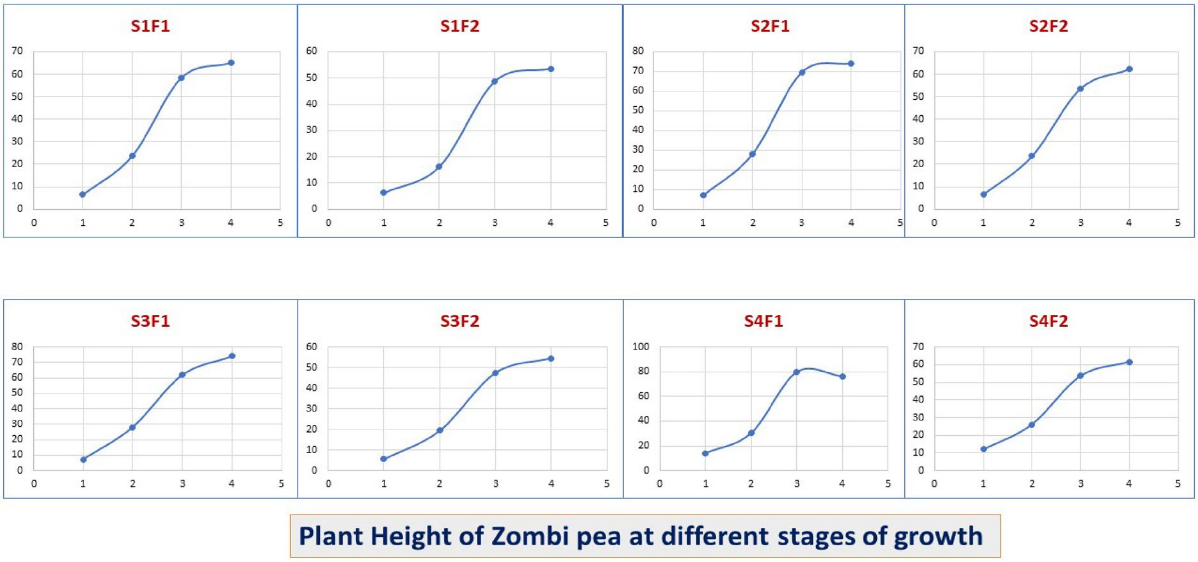

Fig. 7. Impact of plant spacing and deblossoming on plant height at 30, 60, 90 and 120 days after sowing.

Treatment	Tuber length (cm)	Tuber girth (cm)	Tubers per plant	Tuber yield per plant(g)	Tuber yield per ha(q)	Fresh weight of tuber (g)	Dry weight of tuber (g)
Main plot (Spacing)							
S_1 (45 cm × 15 cm)	13.70	14.49	1.70	97.50	150.85	260.39	94.08
S_2 (45 cm × 30 cm)	14.92	15.33	2.20	113.33	115.18	282.05	105.43
S_3 (60 cm × 15 cm)	13.75	14.67	2.05	107.21	90.74	270.61	98.50
S_4 (60 cm × 30 cm)	16.17	16.08	2.60	121.85	66.66	322.39	107.08
SE(m) ±	0.708	0.221	0.084	4.173	5.370	8.569	6.286
C.D. at 5%	NS	0.780	0.296	14.723	18.962	30.230	NS
CV (%)	5.92	1.79	4.81	4.65	6.21	3.70	7.60
Sub plot (Deblossoming)							
F_1(Deblossoming)	16.07	16.39	2.47	129.94	120	363.02	124.55
F_2(Blossom retention)	13.20	13.89	1.81	90.00	90.74	204.69	77.99
SE(m) ±	0.372	0.561	0.086	3.412	3.814	15.529	3.585
C.D. at 5%	1.233	1.859	0.283	11.298	12.666	51.427	11.873
CV (%)	6.23	9.08	9.84	7.60	8.87	13.40	8.67
Interactions							
S_1F_1	14.18	15.38	1.80	124.00	158.14	349.65	114.05
S_1F_2	13.22	13.60	1.60	71.00	143.70	171.12	74.10
S_2F_1	16.22	16.64	2.70	130.65	141.85	372.53	149.93
S_2F_2	13.62	14.02	1.70	96.00	88.88	191.56	60.93
S_3F_1	15.03	15.21	2.30	128.42	103.70	333.38	122.62
S_3F_2	12.46	14.12	1.80	86.00	77.77	207.84	74.38
S_4F_1	18.84	18.33	3.06	136.70	76.66	396.53	111.60
S_4F_2	13.50	13.82	2.13	107.00	56.66	248.24	102.55
SE(m) ±	0.9415	0.568	0.133	6.140	7.592	17.846	8.483
C.D. at 5%	NS	NS	NS	NS	NS	NS	26.244
CV (%)	22.29	13.00	21.57	19.34	24.83	26.67	28.88

Table 2. Influence of plant spacing and deblossoming on tuber yield and related attributes.

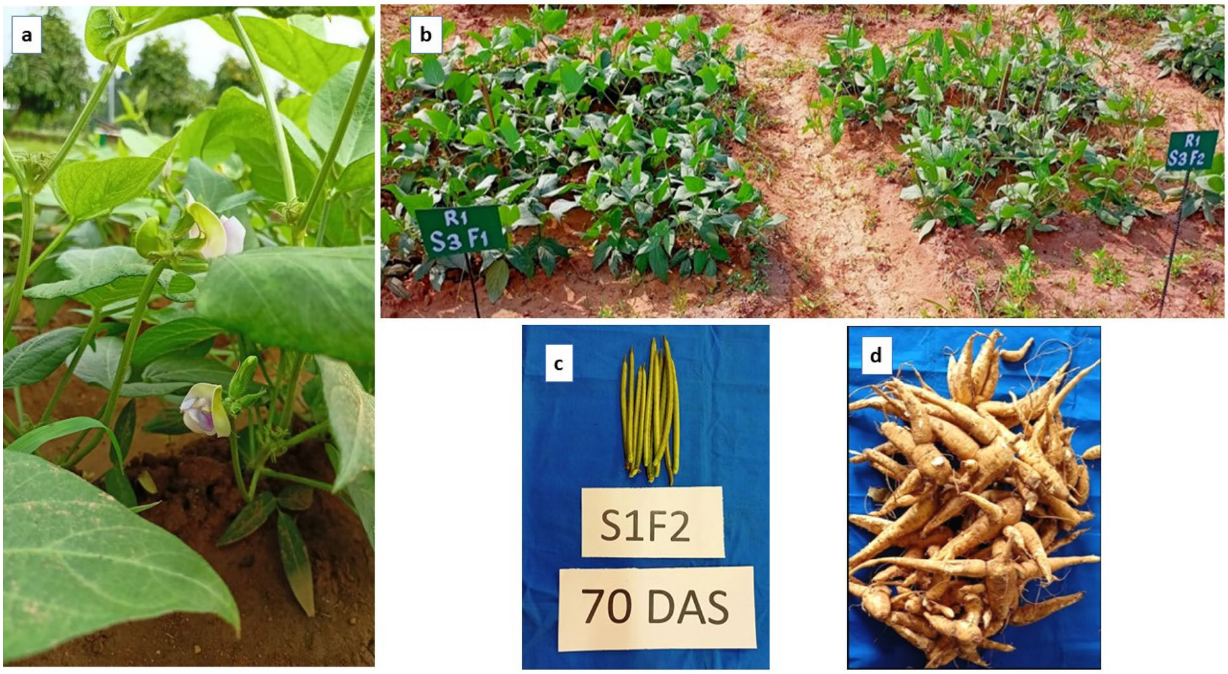

Fig. 8. Morphological features of zombi pea. (**a**): Plant of zombi pea with young flower buds and flowers. (**b**) Field view at different treatments. (**c**) Green pods of zombi pea at 70 days after sowing. (**d**) Harvested tubers of zombi pea.

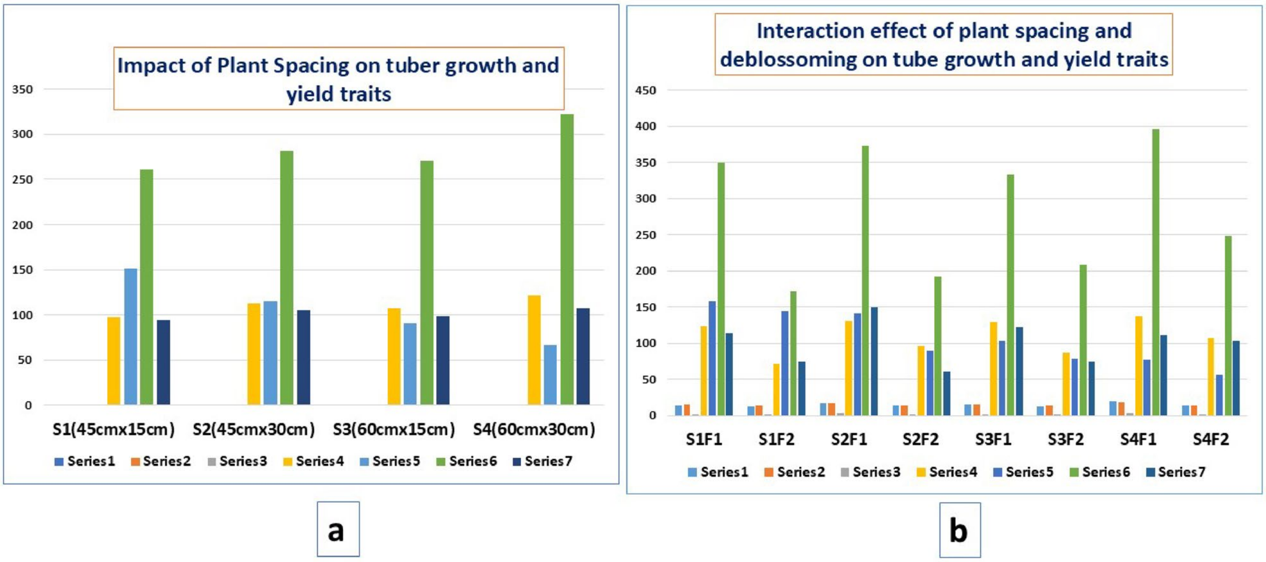

Fig. 9. **(a)** Impact of plant spacing on tuber growth and yield traits. The set of series with different colour denotes tuber growth and yield variables (Series 1: tuber length, series 2: tuber girth, series 3: tubers/plant, series 4: tuber yield/plant, series 5: tuber yield/ha, series 6: fresh weight of tuber, series 7: dry weight of tubers). **(b)** Impact of plant spacing and deblossoming interaction on tuber growth and yield attributes.

Treatment	Green pod length (cm)	Green pod weight (g)	Green pod yield (q/ha)
Main plot (Spacing)			
S_1(45 cm × 15 cm)	6.69	1.59	3.46
S_2(45 cm × 30 cm)	6.58	1.67	2.74
S_3(60 cm × 15 cm)	6.58	1.50	2.65
S_4(60 cm × 30 cm)	6.41	1.58	2.37
SE(m) ±	0.201	0.087	0.143
C.D. at 5%	NS	NS	0.505
Sub plot (Deblossoming)			
F_1 (Deblossoming)	0.00	0.00	0.00
F_2(Blossom retention)	13.13	3.17	5.61
SE(m) ±	0.157	0.076	0.135
C.D. at 5%	0.521	0.253	0.447
Interactions			
S_1F_1	0.00	0.00	0.00
S_1F_2	13.37	3.182	6.92
S_2F_1	0.00	0.00	0.00
S_2F_2	13.16	3.35	5.48
S_3F_1	0.00	0.00	0.00
S_3F_2	13.16	3.00	5.30
S_4F_1	0.00	0.00	0.00
S_4F_2	13.13	3.16	4.74
SE(m) ±	0.292	0.131	0.2205
C.D. at 5%	NS	NS	0.862

Table 3. Effect of spacing and deblossoming on green pod length, weight and yield in zombi pea.

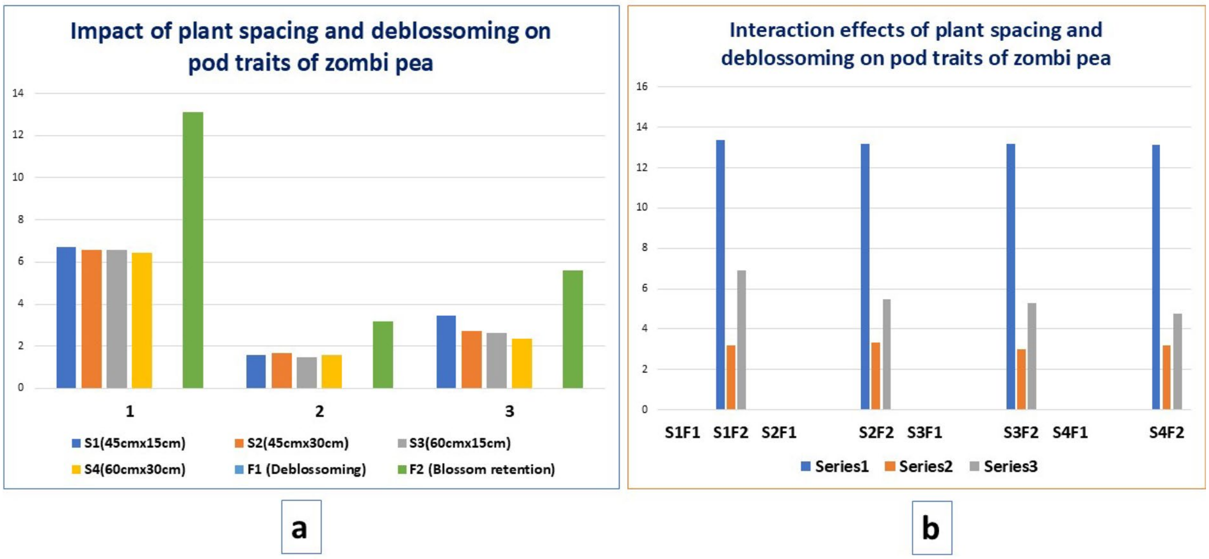

Fig. 10. (**a**) Impact of plant spacing on pod yield, pod length and pod weight of zombi pea. (**b**) Interaction effects of plant spacing and deblossoming treatments on pod yield, pod length and pod weight of zombi pea.

Plant density alters green pod yield and related traits

The data analysis revealed that zombi pea pod length and green pod weight were independent of spacing treatments (Table 3, Fig. 10). The highest green pod length observed in the zombi pea genotype under study was 13.13 cm (Table 3). Similarly, the green pod weight recorded was 3.17 g. The interaction effects of spacings and flowering did not significantly influence the length of green tender pods and the weight of green pods. The significantly highest green pod yield (3.46 q/ha) was recorded in the closer spacing (S_1: 45 cm × 15 cm) than in the wider spacing. The interaction of close spacing and flower retention treatments (S1F2) influenced the green pod yield and recorded an average yield of 6.92 q/ha (Table 3).

Interaction analysis between spacing and deblossoming treatments for phenotypic traits

The results pertaining to association analysis revealed both positive and negative correlation between the studied phenotypic traits (Fig. 11a, b) (Supplementary Tables S2, Table S3). The plant heights at different duration exhibited significantly positive correlation with area and deblossoming condition. The plant girth was negatively associated with spacing and plant heights at different intervals. The plant girth also exhibited significantly negative correlation with all the phenotypic traits under study. Branches per plant expressed a positive correlation with spacing, plant heights, leaves per plant, leaf area, leaf area index and fresh weight, but exhibited a negative correlation with dry weight. Dry weight of leaf and stem was positively correlated with spacing, leaf area index and fresh weight of leaf and stem. Fresh weight of leaf and stem expressed a positive association with majority of phenotypic traits except plant girth. Leaf area index and leaf area per plant expressed a significantly positive association with plant spacing and flower removal condition. Likewise, when flowers were retained, the plant spacing exhibited significant positive correlation with majority of the phenotypic traits except plant girth (Fig. 11b, Table S3). Plant girth was negatively associated with all the phenotypic traits under study except with the plant height at 90 and 120 days after planting. Leaf area index (LAI) expressed a significantly positive correlation with plant spacing, plant heights, fresh weight of leaf and stem, dry weight of leaf and stem, while LAI was negatively associated with plant girth. The positive association of LAI with plant height under wider spacing × deblossoming condition indicates more vegetative expansion that may enhance photosynthetic surface area. The interaction analysis also indicated the significant competition between phenotypic and reproductive sinks under flower retention condition. Overall, the analysis revealed a source-sink trade-off altered by deblossoming. Thus, the agronomic management practices can manipulate the crop performance.

Appraisal of interaction between spacing and deblossoming treatments for tuber yield traits

Both positive and negative correlation was recorded between tuber yield traits at variable spacing and flower retention or deblossoming conditions (Fig. 12a, b) (Supplementary Table S4, Table S5). Plant spacing was positively correlated with tuber length, tuber girth, tuber numbers per plant, tuber yield per plant and tuber fresh weight, while it was negatively correlated with total tuber yield under deblossoming treatments. Likewise, tuber fresh weight expressed positive association with plant spacing, length of tubers, numbers of tubers per plant and yield of tubers obtained per plant. Tuber yield per plant was positively associated with plant spacing and tuber length, tubers per plant and tuber girth. The wide spacing allowed to accumulation of more of vegetative assimilates which strongly translated into higher yield potential per plant. Overall, the correlation analysis patterns support the source-sink influence of deblossoming through which more source capacity benefits tuber yield.

When flowers were retained, both positive and negative correlation was recorded between tuber and pod yield and related traits (Fig. 12 b, Table S5). When flowers were retained, plant spacing exhibited positive association with tuber length, tuber girth, tubers per plant and tuber yield per plant, while negative correlation was expressed with total tuber yield. Plant spacing expressed a negative correlation with green pod length and pod yield. Green pod yield exhibited a negative correlation with majority of tuber traits under study. Tuber fresh weight expressed a positive interaction with numbers of tubers and tuber yield per plant. Tuber dry weight was positively correlated with tuber fresh weight and tuber numbers per plant.

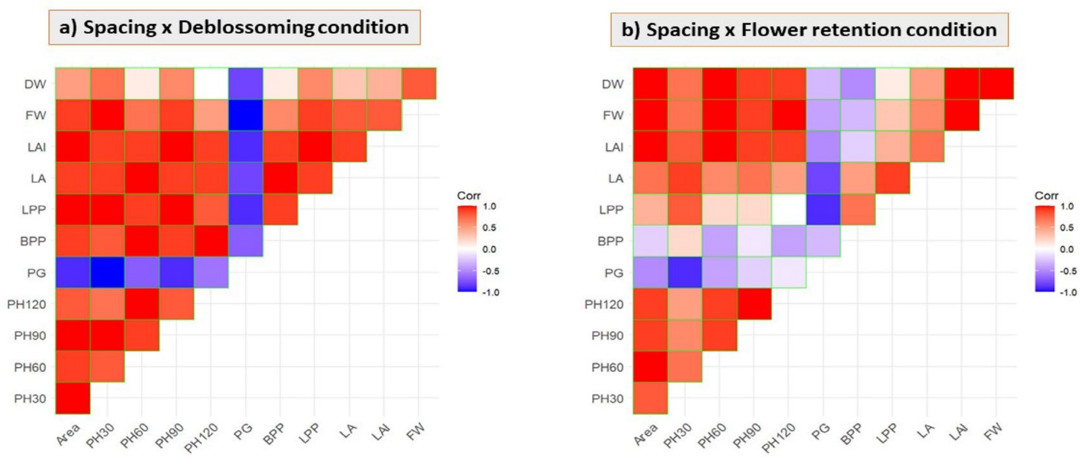

Fig. 11. Pearson's correlation coefficients for phenotypic traits evaluated under variable plant spacing and flower removal or retention conditions. Positive correlation is indicated by intense orange colour and negative correlation by intense blue colour. a): correlation analysis for phenotypic traits between spacing and deblossoming treatments. b): correlation analysis for phenotypic traits between spacing and flower retention treatment. PH: plant height, PG: plant girth, BPP: branches per plant, LPP: leaves per plant, LA: leaf area, LAI: leaf area index, FW: fresh weight of leaf and stem.

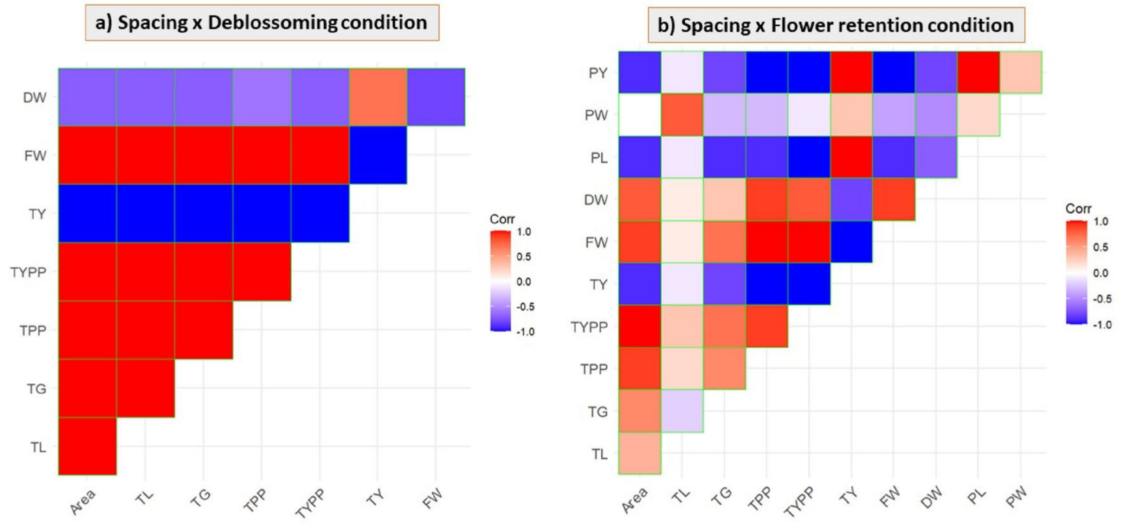

Fig. 12. Pearson's correlation coefficients for tuber yield and related traits tested under variable plant spacing and flower removal or retention conditions. Positive correlation is indicated by intense orange colour and negative correlation by intense blue colour. a): correlation analysis for tuber traits between spacing and deblossoming treatments. b): correlation analysis for tuber and pod traits between spacing and flower retention treatment. TL: tuber length, TG: tuber girth, TPP: tubers per plant, TYPP: tuber yield per plant, TY: total tuber yield/ha, FW: fresh weight of tuber, PL: green pod length, PW: green pod weight.

Treatments	Yield(q/ha)		Gross income (Rs. /ha)		Grand total income (Rs. /ha)	Total cost of cultivation (Rs. /ha)	Net income (Rs. /ha)	Benefit/ Cost ratio
	Tuber	Green pod	Tuber	Green pod				
S_1F_1	15,814	0	158,140	0	158,140	60,932	97,208	2.60
S_1F_2	14,370	692	143,700	13,840	157,540	60,132	97,408	2.62
S_2F_1	14,185	0	141,850	0	141,850	60,932	80,918	2.33
S_2F_2	8888	548	88,880	10,960	99,840	60,132	39,708	1.66
S_3F_1	10,370	0	103,700	0	103,700	60,932	42,768	1.70
S_3F_2	7777	530	77,770	10,600	88,370	60,132	28,238	1.47
S_4F_1	7666	0	76,660	0	76,660	60,932	15,728	1.26
S_4F_2	5666	474	56,660	9480	66,140	60,132	6008	1.09

Table 4. Economics of treatments.

Economics of treatment effects on zombi pea

Highest gross income from the tuber production of zombi pea was estimated in S_1F_1 (close spacing with deblossoming condition) (Rs.158140/ha), while in S_1F_2 (close spacing with flower retention) (Rs.143700/ha) and S_2F_1 (Rs.141850/ha) treatments relatively less gross income was recorded than S_1F_1 (Table 4). Highest gross income from green pod was obtained in the close spacing when flowers were retained (S_1F_2) (Rs.13840/ha). Interestingly, the gross income from green pod production declined with the increase in spacing, viz. S_2F_2 (Rs.10960/ha) and S_3F_2 (Rs.10600/ha) treatments (Table 4). The S_1F_1 treatment yielded the highest grand total income (Rs. 158,140/ha), with S_1F_2 (Rs. 157,540/ha) and S_2F_1 (Rs. 141,850/ha) treatments also resulting in high total incomes (Table 4). Overall, the economic evaluation indicated that higher gross income was obtained with close spacing under flower retention and deblossoming conditions with respect pod yield and tuber yield, respectively. Thus, dual benefits can be harvested from zombi pea through pods and tubers. From farmers' perspective, the incorporation of zombi pea in agricultural production system can maximize returns per unit area. The farmer training initiatives and inclusion of this wonder crop in seed distribution systems can boost the economic returns of farmers, provided region specific crop management practices have been standardized.

Discussion

Vegetable crops, comprising root and tuber crops, bulb crops, leafy vegetables, fruit vegetables, salad vegetables, and tree vegetables, are the essential component of food and nutritional security[5,44–47]. Among the vegetable crops, the legume vegetables are playing a crucial role in enhancing food and nutritional security in face of climate change[4,5,48]. The orphan legumes are the treasure trove of genes for nutritional quality and climate resilience[4,5]. Realizing the potential of orphan legumes, the current investigation was undertaken to understand the crop phenotype and yield potential of zombi pea. The present investigation revealed the significant influence of plant spacing and deblossoming on growth, physiology, plant phenotype and yield attributes of zombi pea. It is evident that plant spacing is the most crucial component in enhancing the crop plant structure and photosynthetic potential[49]. Plant density has an influence on plant phenotypic traits like plant height, crop maturity and yield. Plant density also influences moisture availability and light penetration within plant canopy. The higher the plant density, more is the moisture availability and lower is the light penetration[50]. This interplay significantly affects the plant growth and development, competition and ecological dynamics. In the current study, the wider spacing and minimum number of plants per plot in S_4 (60 cm × 30 cm) treatment might have enabled each plant to uptake nitrogen more efficiently including other nutrients from the soil, thereby resulting in the tallest plants with greater fresh weight of leaf and stem, more tubers per plant and high fresh weight of tuber. Previously, Priyadarsini et al.[7] also reported the effect of wider spacing on nutrient status of zombi pea. The wider spacing resulted higher accumulation of nutrients and tuber protein content[4,7]. The wider spacing allows more light penetration, less competition for nutrients and other inputs, and a better circulation of air[51]. The better yield, growth, physiology, and morphology of zombi plants at the wider spacing is also attributed to less competition between plants for space, light and nutrients[4,52]. The close spacing of 45 cm × 15 cm (S_1) resulted in the maximum tuber yield per unit area, due to high plant density in S_1 condition. The narrow plant spacing enhances plant density that stimulates higher light interception and optimum land use[51]. The increase in plant population under narrow spacing increases the crop yield, although it may increase the competition for various inputs[51]. But the closer spacing also reduces the competition with weeds. The present findings corroborate findings of other researchers on sweet potato[53–55]. The results are also in conformity with the tuber yield of yam bean[56,57]. There is natural competition among the plants after their emergence; therefore, to achieve the higher yield alteration of planting density is practiced accordingly in the field. However, the plants may be stressed with narrow spacing under suboptimal conditions. The planting density is practically important for the growth and development of legume vegetables[58]. Similarly, in a study on cluster beans, the wider spacing exhibited the maximum plant height, number of pods per plant, pods per cluster, LAI, number of grains per pod, and grain yield[52]. The optimum plant nutrient uptake and temperature conditions were reported to be the reason for the increase in growth, physiology, and yield attributes of cluster bean[52]. Previously, our group presented a detailed analysis of the effect of variable plant density and flower retention or deblossoming on the nutritional aspects of zombi pea[7]. In principle, the yield does not increase linearly with an increase in planting density due to competition among the plants for different nutrients and other growth factors[58]. The plant growth and physiological attributes (LAI, LAD, CGR, AGR, NAR) calculated in the current study explain the effect of different treatments or agronomic practices on plant growth and yield potential.

The overall highest green pod yield derived with the closest spacing of 45 cm × 15 cm (S_1) could be attributed to the highest plant density per unit area of land. The results obtained in the current investigation are in line with those of several researchers who proved that closer spacings produced the maximum yields of cowpea[59–63]. The same trend was confirmed in relation to French bean[64–67]. Even at the same spacing, tuber yield/plant was much higher than green pod yield/plant. Ojelade et al.[68] suggested that enhanced yield of groundnut in close intra-row spacing is attributed to the decreased competition with weeds for different resources like light, nutrients, and space. When a zombie pea plant retains both tubers and flowers, the assimilates pertaining to carbon and nitrogen are not equally partitioned and translocated among different parts[7]. In that scenario, more carbon-based photo assimilates are transferred to the underground root tubers, and more nitrogen-based assimilates are transferred to the fruits in larger proportions.

The zombi pea's flower and pod development inhibits its vegetative growth and tuber yield; this may be due to the fact that distinct plant organs directly compete with one another for photosynthates, which are linked to food reserves[37]. Sucrose is the predominant sugar in legume crops, and amino acids are nitrogenous solutes[69]. The phloem transports sugars and other macromolecules to the heterotrophic plant organs[70]. The unloading of solutes in sinks is thought to be facilitated by the difference in osmotic pressure between the phloem and the surrounding tissues[70]. Tall plant height and vigorous vegetative traits under deblossoming conditions could be explained by the fact that deblossoming (F_1) definitely arrested the reproductive growth and encouraged more vegetative growth leading to more plant height, plant girth, branches per plant, leaves per plant, fresh weight of leaf and stem, dry weight of leaf and stem, leaf area per plant, and LAI. Since deblossoming (F_1) hindered the reproductive growth, it also encouraged more translocation of photosynthates to the roots, resulting in longer and thicker root tubers as well as more tuber yield per plant. In the present investigation, the significantly highest tuber yield was recorded in the case of blossom removal (F_1) than blossom retention (F_2) condition. Removal of blossoms might have conserved a part of the plants food reserves and energy, which were then ideally translocated to the root tubers resulting in higher yields. Similar findings of increased tuber yield by deblossoming were also reported on sweet potato and yam bean[71,72]. Thus, it is indicated that reproductive modification accompanied with plant density optimization can significantly affect the marketable yield and quality attributes. The findings of present investigation offer valuable agronomic management insights for adoption of this wonderful crop in the marginal environments. Further elaborative studies are to be done in the future experiments comprising multi-location, multi-year testing under diverse climatic conditions to develop robust agronomic management recommendations for farmers.

Conclusion

The present investigation clearly demonstrated the influence of variable plant spacings and deblossoming on growth, morpho-physiology, pod, and tuber yield related traits in zombi pea. The wider spacing (60 cm × 30 cm) can be followed to increase the plant growth and phenotypic potential, which results in maximum plant height, fresh weight of leaf and stem, tubers per plant (2.6), tuber weight (322.39 g), tuber length (16.17 cm), tuber girth (16.08 cm) and tuber yield/plant (121.85 g). While close spacing of 45 × 15 cm is significantly ideal to obtain the highest total green pod yield (3.46 q/ha) and total tuber yield (150.85 q/ha). Deblossoming (F_1) encouraged more vegetative growth, leading to more plant height, plant girth, branches per plant, leaves per plant, fresh weight of leaf and stem, dry weight of leaf and stem, leaf area per plant, LAI, longer and thicker root tubers with the highest tuber yield per plant and per hectare (120 q/ha). Overall, the improvement in crop physiology (LAR, LAD, AGR, CGR, NAR) was achieved with close spacing of 45 × 30 cm. The present investigation on zombi pea revealed that wider spacing (60 cm × 30 cm) is ideal to achieve the high tuber yield and better plant phenotype, while the close spacing (45 × 15 cm) should be followed to improve the total pod and tuber yield and crop physiology. Additionally, the histology investigations would be helpful in analysing how the conditions of blooming and deblossoming change in relation to phloem development and flowering state in zombie peas. Further, multi-location and multi-year trials based on agronomic practices are required for better recommendations to farmers in their respective locations. The strategic manipulation of crop management practices and reproductive sinks can be effective in optimizing the crop and quality. Zombi pea is a promising commercial crop for addressing the issue of malnutrition in tropical regions like India, which may also prove to be a boon to food security and higher farmer income.

Data availability
All data generated or analyzed during this study are included in this published article.

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