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Research Paper

Residual effect of maize (*Zea mays*) + blackgram (*Vigna mungo*) intercropping on growth, factor productivity and resource-use efficiency of succeeding wheat (*Triticum aestivum*) under integrated crop management

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ABSTRACT

A 2-year field experiment was conducted during the winter (*rabi)* season of 2019–20 and 2020–21 at the ICAR–Indian Agricultural Research Institute, New Delhi to study residual effect of the preceding blackgram (*Vigna mungo* (L.) Hepper) intercropped maize (*Zea mays* L.) on succeeding wheat (*Triticum aestivum* L.) growth, factory productivity, resource-use efficiency, and yields. The treatments consisting of 9 integrated crop management (ICM) variants allotted to mainplots and 2 cropping systems (maize–wheat; maize+blackgram–wheat) in subplots, were replicated thrice in a split-plot design. Different combinations of tillage, crop-establishment patterns, integrated nutrient, weed, pest, and disease management were used to create the integrated crop management (ICM) treatments. The conservation agriculture (CA) embedded ICM, viz. ICM_7, Zero-till + Permanent raised beds + maize crop-residue retention at 3 t/ha + 100% RDF + Glypho-PP fb Sulf+Met at PoE + 4 irrigations of 45 mm each + Need-based IDM/IPM recorded significantly higher growth (99.9 cm), dry-matter accumulation (1127 g/m^2), growth indices (crop growth rate 18.1 g/m^2/day), production (37.5 kg/ha/day)-, monetary (627.8 INR/ha/day)-efficiencies, irrigation water productivity (2.57 kg/m^3) and wheat grain yield (5.57 t/ha). While conventional tillage (CT)-based treatments recorded significantly higher partial factor productivity (57.2, 265.8, 206.6 kg grain/kg of applied N, P and K respectively). The succeeding wheat crop benefited significantly from the residual effect of preceding blackgram intercropping in terms of growth, resource-use efficiency (irrigation water productivity, 2.07 kg/m^3) and productivity (5.16 t/ha). The factor productivity, resource-use efficiency, grain yield of wheat under CA-based ICM can be enhanced by preceding blackgram + maize intercropping.

Key words: Blackgram intercropping, Conservation agriculture, Factor productivity, Integrated crop management, Residual effect, Resource-use efficiency

Wheat (*Triticum aestivum* L.) is cultivated on 31.6 million hectares (ha) in India, with a production of 109.5 million tonnes (t) and an average productivity of 3.46 t/ha (Economic Survey, 2022). It is one of the most important crops in India for anchoring country's food security. However, the farming community is confronted with a slew of issues, including soil degradation, water shortages, insect and disease comeback, the introduction of resistant weeds, and low resource-use efficiency, per se. Climate change, in addition to these issues, has a multifaceted detrimental influence on agriculture jeopardising the long-term food security. Thus, enhancing agricultural production, profitability, and resource efficiency has become a key focus of research for improving farmers' livelihoods (ICAR, 2015). Wheat output can be increased in 2 ways. First, horizontal intensification by bringing additional land under wheat production, which appears less likely due to increased land degradation, increased soil issues (salinization and alkalization), conflicting land-use requirements, and so on. Second, by increasing wheat productivity, which appears to be feasible; nevertheless, depletion of natural resources, low resource-use efficiency, poor soil fertility, and a large productivity gap between research farms and farmers' fields are important hurdles in the improvement of wheat produc-

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tivity (Majumdar *et al*., 2012). This highlights the need of increasing wheat yield and resource-use efficiency. In order to overcome the afore-mentioned obstacles, alterations in crop-production methods are inevitable. When opposed to conventional tillage (CT) and traditional crop-production practises, which follow a non-integrated approach, conservation agriculture (CA) and integrated crop management (ICM) might be beneficial in resolving some if not all of these issues.

Furthermore, the FAO report on achieving sustainable development goals in agriculture emphasizes the need of an integrated crop-production system to accomplish zero hunger and climate change action (mitigation and adaptation). Integrating ICM and legume intercrop in a CA system is expected to increase soil health, reverse land degradation, and reduce biodiversity loss, among the key benefits. These techniques may help grow the rural economy and the economy of country as a whole, besides supporting a resilient and sustainable cropping environment (FAO, 2018).

Integrated crop management is a versatile, field-specific crop-production system that aids in enhancing crop-productivity and reducing input consumption by integrating all crop-management strategies. In crop production, ICM employs a relevant mix of several crop-specific management strategies, such as an integrated form of crop establishment technique, tillage, fertilizer, weed, and water management (Varatharajan *et al*., 2019a; Choudhary *et al*., 2020). Thus, ICM has a dual benefit of increasing crop output besides improving input-use efficiency. There is little information available on the residual effect of maize + blackgram intercropping on subsequent wheat crop growth, different factor productivities, and crop efficiencies especially under ICM approach. Hence current investigation was planned and conducted to assess how wheat crop fared after the preceding cereal + legume intercropping system in terms of growth, factor productivity, nutrient harvest index, efficiency, and productivity.

MATERIALS AND METHODS

The field experiment was conducted during the winter (*rabi*) seasons of 2019–20 and 2020–21 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi (28°63' N; 77°15' E), representing trans-gangetic plains region of Indo-Gangetic Plains Region (IGPR). During 2-year experimentation, the mean maximum and minimum temperature, daily pan evaporation recorded were 25.2°C, 10.5°C and 2.8 mm/day respectively, while 301.7- and 74.3-mm total rainfall received during the cropping season of 2019–20 and 2020–21 respectively. The experimental site was sandy loam, having soil *p*H 8.2, organic carbon 0.486% and 194, 15 and 303 kg/ha available nitrogen, phosphorus and potassium respectively. The experiment was laid out in a split-plot design with 3 replications, where 9 ICM practices in mainplots; these ICM practices consist combination of various tillage, crop establishment, residue retention, integrated nutrient-, weed-, disease-, pest-management approaches. The details of 9 ICM main-plot treatments are: ICM_1, conventional tillage (CT) + flat-beds (FB) + 100% of recommended dose of fertilizers (RDF) at 120 : 60 : 40 kg N : P_2O_5 : K_2O/ha + sulfosulfuron (Sulf) + metsulfuron (Met) PoE at 40 g/ha as post-emergence (PoE) at 25 DAS + 4 irrigations of 60 mm each + need-based integrated disease management (IDM) / integrated pest management (IPM); ICM_2, CT–FB + 75% RDF at 90 : 45 : 30 kg N : P_2O_5 : K_2O/ha + arbuscular mycorrhizal fungi (AMF) at 12.5 kg/ha + NPK-biofertilizers (NPK-bf) + Sulf+Met at PoE + 4 irrigations of 60 mm each + need-based IDM/IPM; ICM_3, CT + raised-beds (RB) + 100% RDF + Sulf+Met at PoE + 4 irrigations of 45 mm each + need-based IDM/IPM; ICM_4, CT–RB + 75% RDF + AMF + NPK-bf + Sulf+Met at PoE + 4 irrigations of 45 mm each + need-based IDM/IPM; ICM_5, zero-tillage (ZT) + FB + maize crop-residue retention (CRR) at 3 t/ha + 100% RDF + glyphosate pre-planting (PP) at 1 kg a.i./ha 15 days prior to sowing fb Sulf+Met at PoE + 4 irrigations of 60 mm each + need-based IDM/IPM; ICM_6, ZT–FB + CRR @ 3 t/ha + 75% RDF + AMF + NPK-bf + glypho-PP fb Sulf+Met at PoE + 4 irrigations of 60 mm each + need-based IDM/IPM; ICM_7, ZT + permanent raised-beds (PRB) + CRR at 3 t/ha + 100% RDF + glypho-PP fb Sulf+Met at PoE + 4 irrigations of 45 mm each + need-based IDM/IPM; ICM_8, ZT–PRB + CRR at 3 t/ha + 75% RDF + AMF + NPK-bf + glypho-PP fb Sulf+Met at PoE + 4 irrigations of 45 mm each + need-based IDM/IPM; ICM_9, CT–FB + maize crop-residue retention (CRR) at 3 t/ha + FYM at 10 t/ha + AMF + NPK-bf + 1 hand weeding and its mulching at 25 days after sowing (DAS) + 4 irrigations of 60 mm each + need-based organic IDM/IPM. These 9 ICM practices can be grouped into (i) conventional tillage (CT)-based ICM_1 to ICM_4; (ii) conservation agriculture (CA)-based ICM_5 to ICM_8 and (iii) organic agriculture (OA)-based ICM_9.

In order to study and compare the residual effect of preceding legume intercropping on succeeding wheat crop, 2 different cropping systems (CS) were incorporated in subplots i.e. (i) CS without previous legume intercropping [maize (*Zea mays* L.) – wheat (*Triticum aestivum* L.) cropping system (MWCS)], and (ii) CS with previous legume intercropping [maize + blackgram (*Vigna mungo* (L.) Hepper] – wheat cropping system (MBWCS)]. Therefore, in the present study, the wheat crop sown in both subplots received same set of input and management practices, to study the residual effect of previous legume intercropping on succeeding wheat crop from their respective sub-plots.

Wheat variety HD 2967 was sown using 100 kg/ha seed rate at 22.5 cm row-to-row spacing in solid lines in the third week of November each year. In RB/PRB crop establishment, 3 rows of wheat were sown in every bed of 70 cm width. For maintaining desired plant density, thinning and gap-filling were effected 15 days after sowing. Under nutrient-management option, entire quantity of P and K was applied basal and N was applied in 3 equal splits, i.e. basal, crown-root initiation (CRI) and flowering stages respectively. Under 75 % RDF applied treatments, the AMF and NPK-bf were applied before sowing. Number of irrigations were common among all the ICM treatments (4 irrigations applied in 2019–20 and 6 irrigations applied in 2020–21), but the amount of water applied varied among treatments based on crop-establishment pattern followed, i.e. 60 and 45 mm for FB and RB/PRB planting.

The wheat crop samples were collected from the second row of each plot from 2 places at 30-day intervals. The crop-growth parameters like plant height, dry-matter accumulation (DMA); the growth analyses like absolute growth rate (AGR), crop-growth rate (CGR), relative growth rate (RGR) were studied at 30-day intervals from sowing up to harvesting. While harvesting, the crop from net-plot area was harvested and grain and straw yields were recorded and converted into t/ha (Rana *et al*., 2014). The partial factor productivity (PFP, kg grain/kg of applied-nutrient) and nutrient harvest index (NHI, %) for N, P, and K were determined as follows:

$$\text{PFP} = \frac{\text{Grain yield (kg/ha)}}{\text{Amount of nutrient applied (kg/ha)}}$$

$$\text{NHI} = \frac{\text{Nutrient uptake in grains (kg/ha)}}{\text{Nutrient uptake in grains + straw (kg/ha)}}$$

The amount of nutrient applied denotes the total amount of nutrients supplied through fertilizers, crop residues, farmyard manure or in their combination to various ICM treatments as described above. The PFP was calculated individually for different nutrients like N, P, and K. The irrigation water productivity (IWP, kg/m^3), production-efficiency (PE, kg/ha/day), and monetary-efficiency (ME, INR/ha/day) were calculated using the following formulas:

$$\text{IWP} = \frac{\text{Grain yield (kg/ha)}}{\text{Irrigation water applied (m}^3\text{)}}$$

$$\text{PE} = \frac{\text{Grain yield (kg/ha)}}{\text{Duration of crop in days}}$$

$$\text{ME} = \frac{\text{Net return (INR/ha)}}{\text{Duration of crop in days}}$$

The experimental data collected were analysed using analysis of variance (ANOVA) technique and the critical difference (*P*=0.05) value was calculated to identify significant difference among treatments as described by Rana *et al*., (2014).

Table 1. Effect of different integrated crop management and cropping system on wheat plant height and dry-matter accumulation (DMA) at 30-day intervals (pooled mean of 2 years)

Treatment	Plant height (cm)				DMA (g/m^2)			
	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
Integrated crop-management (ICM)								
ICM_1	25.0	49.8	75.3	92.6	27.7	140.0	621.2	993
ICM_2	24.4	47.4	74.4	91.0	26.1	138.5	613.8	994
ICM_3	26.1	51.4	77.1	94.8	30.2	141.0	640.7	1079
ICM_4	25.1	50.9	76.1	93.3	28.8	142.0	638.1	1046
ICM_5	26.7	52.7	78.6	96.3	30.1	147.9	667.9	1080
ICM_6	25.9	51.6	77.5	94.2	31.4	147.2	662.1	1069
ICM_7	27.7	56.8	82.9	99.9	34.4	151.1	694.9	1127
ICM_8	25.9	54.8	79.8	98.5	32.6	147.1	685.4	1110
ICM_9	24.0	44.7	70.8	88.7	23.7	131.4	593.5	949
SEm±	0.1	0.2	0.2	0.2	0.1	0.5	2.4	3.2
CD (P=0.05)	0.3	0.5	0.7	0.7	0.3	1.3	7.0	9.3
Cropping systems								
M–W	24.4	49.3	76.0	93.7	28.7	140.7	640.8	1037
M+B–W	26.9	52.9	77.8	95.0	30.1	145.1	652.0	1063
SEm±	0.03	0.03	0.05	0.04	0.0	0.1	0.3	0.8
CD (P=0.05)	0.08	0.10	0.13	0.12	0.1	0.3	1.0	2.3
Interaction	NS	NS	NS	NS	NS	NS	NS	NS

[a]DAS, Days after sowing.
[b]Details of integrated crop management are given under materials and methods.
[c]M–W, Maize–wheat cropping system; M+B–W, Maize+blackgram–wheat cropping system.

RESULTS AND DISCUSSION

Effect of Integrated crop management

Growth attributes: Integrated crop management had a significant effect on wheat plant height (Table 1). Among the ICM practices, CA-based treatments recorded tallest plants, followed by CT and OA at all measuring intervals. During 30 DAS, ICM_7 [zero-till + Permanent raised-beds + maize crop-residue retention at 3 t/ha + 100% RDF + Glypho-PP fb Sulf+Met at PoE + 4 irrigations of 45 mm each + need-based IDM/IPM] recorded significantly taller plants. The ICM and cropping system interaction was non-significant for plant height. Higher amount of nutrient and moisture availability under CA-PRB modules resulted in taller plants (Kumar and Pal, 2021).

Dry-matter accumulation (DMA) was significantly affected by ICM. Though the 100% RDF-applied ICM practices showed higher DMA than 75% RDF + AMF + NPK-bf-applied ICM treatments, and they were statistically on par with each other. This indicates the synergistic effect of AMF and NPK-bf could fulfil short fall of nutrients for the plots, where 75% RDF was applied. The DMA was in order of CA > CT > OA; while the ICM_7 accumulated significantly higher dry matter/m^2 which was followed by ICM_8 > ICM_5 > ICM_6 > ICM_3 > ICM_4 > ICM_1 > ICM_2 > ICM_9. Similar trend was observed for all measuring intervals like 30, 60, 90, and 120 DAS. During 120 DAS, CA-based ICM_7 treatment accumulated the highest dry-matter (1,127 g dry mater/m^2). The OA-based ICM_9 recorded the least DMA in all measuring intervals, which was 15.5–16.2% lower than the treatment with the highest DMA (ICM_7) at 120 DAS; low nutrient availability, water stagnation in flat-bed during heavy rainfall event, could be the cause for low DMA under ICM_9. The ICM and cropping system had no significant interaction on DMA. Maize crop-residue retention (3 t/ha) under CA treatments, created optimal soil microclimate for microbial activity, N and P cycle-solubilization and mineralization of nutrients (Singh *et al*., 2021) and support its activity by providing carbon source. Besides, nutrients released from residue decomposition further benefit the wheat crop by continuous supply of nutrients (Jayaraman *et al*., 2021).

Growth analysis: The ICM practices influenced significantly all crop-growth indices in wheat like AGR, CGR and RGR (Table 2). The AGR initially increased up to 30–60 DAS, then began to taper down as the crop advanced towards maturity. The ICM exerts significant influence on AGR only during 0–30, 30–60 DAS, and later becomes non-significant. Wheat crop under ICM_7, a CA-PRB treatment, grew at the rate of 0.97 cm/day during 30–60 DAS, which was the highest AGR observed among the treatments and at all measuring intervals, where OA-ICM_9 showed the least AGR(0.69 cm/day) during 30–60 DAS.

Wheat-crop growth rate steadily increased up to 60–90 DAS and later decreased with the increasing age of crop. During 60–90 DAS, the wheat crop under ICM_7 treatment grew at rate of 18.1 g/m^2/day, being 11.6–12.1% and 14.4–15.9% significantly higher than CT and OA-based treatments. During 60–90 DAS, the least CGR was recorded in OA-ICM_9 (15.4 g/m^2/day). In all measurement intervals up to 60–90 DAS, CA-based ICM treatments had significantly superior CGR to that of CT and OA (Table 2).

The ICM treatments influenced RGR of wheat only during early stages of development till 60 DAS; later the changes in RGR caused by ICM were non-significant (Table 2) (Harish *et al*., 2021). During 0–30, the CA-ICM_7 exhibited significantly higher RGR (117.9 mg/g/day), which was 6.1–6.2% and 10.6% greater than CT and OA-based treatments respectively; and the highest RGR found in CA followed by CT and OA. However, during 30–60 DAS, OA-ICM_9 resulted in significantly higher RGR (57.2 mg/g/day), while the highest RGR found in OA, followed by CT and CA. From 60 DAS till harvesting, ICM had no significant effect on RGR. The ICM and CS did not show significant interaction for all growth indices for all measuring intervals.

Partial factor productivity and nutrient harvest index: The PFP of N, P, and K were significantly influenced by the ICM (Table 3). Irrespective of study year, the PFP_N was in the order of ICM_4 > ICM_9 > ICM_2 > ICM_8 > ICM_6 > ICM_3 > ICM_7 > ICM_5 > ICM_1. The CT+RB-based ICM_4 treatment produced 57.2 kg grain/kg of N-applied, that was highest among ICM treatments. The least PFP N was observed in CT+FB-based ICM_1 (38.8 kg grain/kg N-applied).

The PFP P was in the order of ICM_4 > ICM_2 > ICM_8 > ICM_6 > ICM_3 > ICM_7 > ICM_5 > ICM_1 > ICM_9. The CT+RB-based ICM_4 treatment had produced 265.8 kg grain/kg of P-applied, which was highest among ICM treatments.The least PFP_P observed in OA-based ICM_9 (132.8 kg grain/kg P-applied).

The CT-based ICM treatments had significantly higher PFP K than CA and OA. The additional amount of K supplied from maize-crop residue retained in CA and OA-based treatments, reduced PFP K of these modules.The PFP K was in the order of ICM_4 > ICM_2 > ICM_3 > ICM_1 > ICM_8 > ICM_6 > ICM_7 > ICM_5 > ICM_9, Varatharajan *et al*., (2019a) already reported similar results. The CT+RB-based ICM_4 treatment had produced 206.6 kg grain/kg K-applied, which was the highest among ICM treatments respectively. Similarly, the least PFP K observed in OA-based ICM_9 (45.1 kg grain/kg K-applied). The interaction between ICM and CS was non-significant for PFP N and P, while it was significant for PFP K. This might be attributed to the additional time needed to see the residual influence of earlier legume intercropping on ICM-CS interaction for PFP N and P.

Table 2. Effect of integrated crop management and cropping system on absolute growth rate (AGR), crop-growth rate (CGR) and relative growth rate (RGR) in wheat at 30-day intervals (pooled mean of 2 years)

Treatment	AGR (cm/day)				CGR (g/m^2/day)				RGR (mg/g/day)			
	0–30 DAS	30–60 DAS	60–90 DAS	90–120 DAS	0–30 DAS	30–60 DAS	60–90 DAS	90–120 DAS	0–30 DAS	30–60 DAS	60–90 DAS	90–120 DAS
Integrated crop-management (ICM)												
ICM_1	0.83	0.83	0.85	0.58	0.92	3.75	16.0	12.4	110.6	54.1	49.7	15.7
ICM_2	0.81	0.77	0.90	0.55	0.87	3.75	15.8	12.7	108.6	55.7	49.6	16.1
ICM_3	0.87	0.84	0.86	0.59	1.01	3.70	16.7	14.6	113.5	51.4	50.5	17.3
ICM_4	0.84	0.86	0.84	0.57	0.96	3.77	16.5	13.6	111.9	53.3	50.1	16.5
ICM_5	0.89	0.87	0.86	0.59	1.00	3.93	17.3	13.7	113.4	53.1	50.3	16.0
ICM_6	0.86	0.86	0.86	0.56	1.05	3.86	17.2	13.6	114.8	51.6	50.1	16.0
ICM_7	0.92	0.97	0.87	0.56	1.15	3.89	18.1	14.4	117.9	49.4	50.9	16.1
ICM_8	0.86	0.96	0.84	0.62	1.09	3.81	17.9	14.1	116.1	50.2	51.3	16.0
ICM_9	0.80	0.69	0.87	0.60	0.79	3.59	15.4	11.8	105.4	57.2	50.3	15.6
SEm±	0.003	0.006	0.004	0.004	0.004	0.01	0.09	0.13	0.13	0.08	0.19	0.15
CD (P=0.05)	0.01	0.02	NS	0.01	0.01	0.04	0.25	0.37	0.38	0.24	NS	NS
Cropping system												
M–W	0.81	0.83	0.89	0.59	0.96	3.73	16.7	13.2	111.6	53.2	50.5	16.0
M+B–W	0.90	0.87	0.83	0.57	1.00	3.83	16.9	13.7	113.3	52.6	50.1	16.3
SEm±	0.001	0.001	0.001	0.001	0.001	0.004	0.013	0.028	0.05	0.06	0.03	0.03
CD (P=0.05)	0.003	0.003	0.003	0.002	0.004	0.011	NS	NS	0.14	NS	NS	NS
Interaction	NS	S	S	0.02	NS	NS	NS	NS	NS	NS	NS	NS

[a]DAS, Days after sowing.
[b]Details of integrated crop management are given under materials and methods.
[c]M–W, Maize–wheat cropping system; M+B–W, Maize+blackgram–wheat cropping system.

The ICM treatments with 75% RDF + AMF + NPK-bf resulted in significantly higher PFP (N, P, and K) than 100% RDF-applied ICM treatments. In general, PFP of all 3 studied elements, under ICM treatments with residue retention (ICM_5 to ICM_9) was significantly lower than non-residue retained, bare soil ICM treatments (ICM_1 to ICM_4). Similarly, CA-based ICM treatments showed lower PFP (N,P, and K) due to additional N, P, and K obtained from decomposition of residue retained. Irrespective of ICM treatments, and various factors like tillage, crop establishment, nutrient management, residue retention, the PFP of all 3 nutrients (N,P, and K) exhibited improvement in the second year of experiment.

The ICM treatments did not affect N- and P-harvest index significantly, while K-harvest index (KHI) was significantly affected (Table 3). The CA-based ICM treatments recorded higher KHI followed by CT and OA. This denotes higher translocation of K to wheat grains under CA. The KHI of 100% RDF-applied plots stood at par with 75% RDF + AMF + NPK-bf; higher soil-available K and improved efficiency of K-solubilizing bacteria in NPK-bf-applied might have played a significant role. The CA+PRB-based ICM_8 had the highest KHI (23.1%), could be owing to higher initial available K content in soil and better translocation from source to sink (Maheta *et al*., 2020).

Resource-use efficiency: The ICM practices significantly influenced production efficiency (PE), monetary efficiency (ME) and irrigation water productivity (IWP). The CA-based ICM_7 produced 37.5 kg grain/ha/day, being 16.1–16.7 and 24.3–24.5% significantly higher than CT+FB and OA respectively (Fig. 1). The OA-ICM_9 recorded least PE of 28.4 kg grain/ha/day.

Similarly, the CA-based ICM_7 earned 627.8 ₹/ha/day, being 14.8–15.2 and 39.8–41.0% significantly higher than CT+FB and OA respectively. The OA-ICM_9 had the least ME of 374.3 ₹/ha/day, respectively. Likewise, higher yield under CA-based treatments resulted in

Table 3. Effect of integrated crop management and cropping system on partial factor productivity (PFP) and nutrient harvest index (NHI) of (N, P, and K) in wheat (pooled mean of 2 years)

Treatment	PFP N (kg grain/kg of applied-N)	PFP P (kg grain/kg of applied-P)	PFP K (kg grain/kg of applied-K)	N-harvest index (%)	P-harvest index (%)	K-harvest index (%)
Integrated crop-management (ICM)						
ICM_1	38.8	180.3	140.1	77.6	65.0	19.3
ICM_2	50.9	236.9	184.1	77.4	64.7	19.6
ICM_3	43.4	202.0	157.0	77.7	66.1	21.4
ICM_4	57.2	265.8	206.6	78.1	66.5	21.7
ICM_5	38.6	180.7	72.7	76.8	65.5	22.9
ICM_6	48.3	227.0	80.7	76.7	64.9	22.6
ICM_7	39.6	185.4	74.6	76.4	66.5	22.6
ICM_8	49.6	233.0	82.9	76.5	65.6	23.1
ICM_9	54.6	132.8	45.1	77.9	64.7	19.1
SEm±	0.2	0.8	0.5	0.14	0.24	0.12
CD (P=0.05)	0.5	2.2	1.4	NS	NS	0.34
Cropping system						
M–W	45.9	201.1	113.6	77.8	65.2	21.1
M+B–W	47.6	208.6	118.4	76.7	65.8	21.7
SEm±	0.0	0.1	0.1	0.02	0.04	0.02
CD (P=0.05)	0.1	0.4	0.3	0.07	NS	0.05
Interaction	NS	NS	S	NS	S	S

[a]DAS, Days after sowing.
[b]Details of integrated crop management are given under materials and methods.
[c]M–W, Maize–wheat cropping system; M+B–W, Maize+blackgram–wheat cropping system

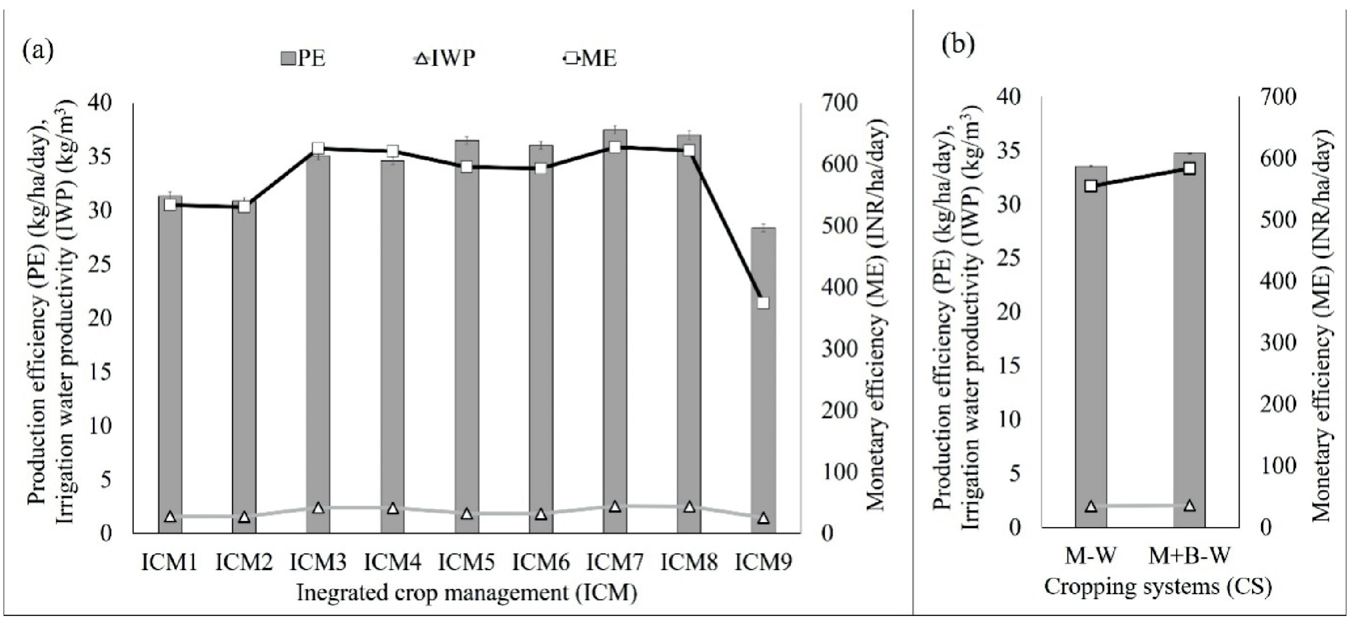

Fig. 1. Effect of integrated crop management and cropping system on resource-use efficiency [production efficiency (PE), monetary efficiency (ME) and irrigation water productivity (IWP)] in wheat (pooled mean of 2 years): Details of integrated crop management are given under materials and methods. M–W, Maize–wheat cropping system; M+B–W, Maize+blackgram–wheat cropping system.

significantly higher PE and ME.

The CA-PRB (ICM_7 and ICM_8) showed significantly higher IWP, followed by CT+RB, CA+FB, CT+FB, and OA+FB (Fig. 1). The CA-based ICM_7 produced 2.57 kg grain/m^3 of irrigation water applied. Residue retention prevents soil evaporation loss, higher yield with less amount of water applied owing to less water loss in CA-based treatments resulted in significantly higher IWP. Our results confirm those of Varatharajan *et al*., (2019b), who confirm that CA-based ICM modules had increased resource-use

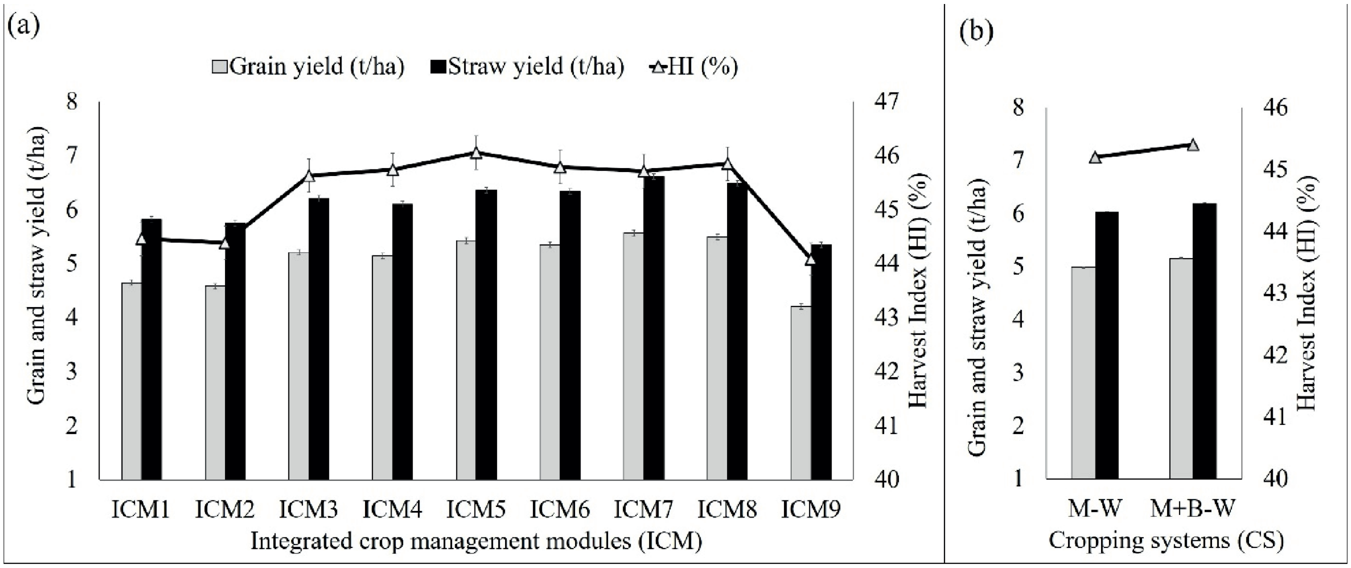

Fig. 2. Effect of integrated crop management and cropping system on grain, straw yields (t/ha) and harvest index (HI) of wheat (pooled mean of 2 years): Details of integrated crop management are given under materials and methods; M–W, Maize–wheat cropping system; M+B–W, Maize+blackgram–wheat cropping system.

efficiency than CT-based modules.

Crop productivity: The ICM treatments had significant effect on grain and stover yields of wheat; while ICM had no effect on harvest index of wheat (Fig. 2). The highest grain yield (5.57 t/ha) was recorded in CA+PRB ICM_7, which was 16.1–16.8 and 24.2–24.3% significantly higher than CT+FB and OA. The grain and stover yields of ICM treatments with 100% RDF stood at par with 75% RDF + AMF + NPK-bf. The ICM treatments with RB/PRB crop establishment were superior to FB. Similarly, the highest stover yield (6.61 t/ha) was recorded in CA+PRB ICM_7, being 11.5–12.6 and 18.7–19.4% higher than CT+FB and OA (Varatharajan *et al*., 2019b). The use of NPK-bf with AMF improved the soil-P availability (Ram *et al*., 2015). As a result, greater P availability allows the wheat crop's root-system to explore a larger volume of soil for nutrients and moisture, resulting in enhanced yield (Mahanta *et al*., 2014). According to Singh *et al*., (2022), CA increases the bacterial population involved in the P-cycle-solubilization and mobilization, which helps improve P absorption and wheat productivity. Retention of maize residue in CA-treatments is beneficial for (i) limiting weed germination/growth, (ii) slow nutrient release from decomposition, and (iii) increasing soil microbial activity by acting as a carbon source for bacteria. All of these elements work together to promote soil fertility and wheat yield (Jayaraman *et al*., 2021).

Residual effect of previous legume intercropping

Growth attributes: The previous legume intercropping exerted significant influence on plant height and DMA of succeeding wheat crop possibly owing to residual effect. Thus, wheat crop under maize+blackgram–wheat cropping system (MBWCS) was significantly taller than wheat under maize–wheat cropping system (MWCS) (Waghmare and Singh, 1984). The residual effect of previous legume intercropping showed gradual decreasing trend with age of wheat crop. On an average, the wheat plants under MBWCS were 9.1, 7.0, 2.3 and 1.4% significantly taller than wheat under MBWCS, during 30, 60, 90 and 120 DAS respectively.Similarly, the wheat plants under MBWCS accumulated 4.8, 3.0, 1.7 and 2.4% higher dry matter, which was significantly higher than wheat under MBWCS during 30, 60, 90, and 120 DAS respectively. On an average at 120 DAS, wheat plants under MBWCS were 95 cm taller with DMA of 1062.7 g/m^2 (Table 1). In terms of DMA, the residual influence from the prior legume intercrop was having a long-term considerable impact in the subsequent wheat crop. Improved plant height and DMA in wheat crop succeeding blackgram (legume) intercropped maize might be owing to atmospheric nitrogen fixation by previous legume intercrop and nitrogen release from root nodule breakdown by previous legume crop (Fustec *et al*., 2010).

Growth analysis: Residual effect of previous legume intercrop had significant influence on succeeding wheat crop only during the initial growth stages. The MWCS and MBWCS differed significantly for AGR up to 60–90 DAS, till then residual effect of previous legume intercrop was prominent (Table 2). Wheat under MBWCS was growing 0.90, 0.85, 0.83 cm/day, while the AGR of wheat under MWCS grew at rate of 0.83, 0.82, 0.90 cm/day during

0–30, 30–60, and 60–90 DAS respectively.

Significant impact of previous blackgram intercropping and its residual effect in the present wheat for CGR was found only during 0–30 DAS (Table 2). From 30 DAS till harvesting, differences between MWCS and MBWCS for CGR were non-significant and both CS considered to be at par. Similar trend was observed in wheat RGR, where the MWCS and MBWCS differed significantly only during initial 0–30 DAS, where MBWCS recorded 1.3–1.6% significantly higher RGR than MWCS (Table 2). It denotes the residual impact of previous legume intercrop was not strong enough to have a long-lasting impact on various growth rates of wheat crop like AGR, CGR and RGR.

Partial factor productivity and nutrient harvest index: The PFP of N, P, and K under MBWCS was 3.7, 3.6 and 4.0% higher than that of MWCS, and the difference was significant. The MBWCS produced 47.6, 208.6 and 118.4 kg grain/kg N-, P-, and K-applied respectively (Table 3). The PFP N of MBWCS was higher than MWCS, emphasizing the significant benefit of residual effect from previous legume intercropping. Higher grain yield obtained, for the same amount of nutrient applied under MBWCS, owing to higher availability of N and P as a result of residual effect of preceding blackgram intercropping, eventually resulted in improving PFP of all 3 applied nutrients (N, P, and K).

The MBWCS significantly influenced N- and K-harvest index owing to residual effect of preceding legume intercrop, while P- harvest index was found non-significant (Table 3). Wheat grains under MBWCS had 1.0–1.3% higher nitrogen harvested in grains than MWCS, owing to residual effect of earlier legume intercrop, while P- and K-harvest index under MBWCS was 2.3 and 5.0% higher than MWCS.

Resource-use efficiency: The MBWCS produced 34.7 kg grain/ha/day, being 3.1–3.8% higher than MWCS. Similarly, MBWCS earned 583.7 INR/ha/day, which was 4.6–5.2% higher than MWCS respectively. The MBWCS produced 2.07 kg grain/m^3 of irrigation water applied, which was 3.8% significantly higher than MWCS, owing to higher wheat yield under MBWCS respectively (Fig. 1).

Crop productivity: The MBWCS resulted in 5.16 t/ha wheat grain yield, being 3.4% significantly higher than MWCS, indicates significant soil-nitrogen enrichment from preceding legume intercrop on succeeding wheat crop, while MBWCS gave 6.19 t/ha wheat stover yield, which was 2.6% higher than MWCS, respectively (Fig. 2). At the same time, cropping has no significant effect on harvest index of wheat. Nitrogen release from decomposition of legume root nodules, solubilization of insoluble P, improved soil physical environment, soil organic carbon, soil microbial activity played synergistic role in improving wheat productivity under MBWCS (Nair *et al*., 1979; Ghosh *et al*., 2007; Panwar *et al*., 2021).

Decomposition of preceding legume root nodules and residues, N rhizodeposition in rhizosphere soil, and atmospheric N fixation in soil (Fustec *et al*., 2010; Amanullah *et al*., 2021; Kebede, 2021) are all extremely helpful towards improving growth and productivity of subsequent wheat crop. Furthermore, using legumes in a cropping system as an intercrop or a sole crop boosts phosphorus availability to the next crop (Arihara *et al*., 1991). Legume crop root exudates (citrate, maleate, carboxylates and others) aid in the solubilization of insoluble P in the soil, making it available to the next wheat crop in the cropping system (Nuruzzaman *et al*., 2005; Zhang *et al*., 2016). In legume intercropped soils, root-induced acidification/ alkalization is beneficial for boosting rhizosphere P availability (Devau *et al*., 2011). Similarly, applying NPK-bf and AMF to the soil might increase P availability and absorption. As a result, greater P availability may strengthen the root-system of wheat crops, allowing them to explore a larger volume of soil for nutrition and moisture (Ram *et al*., 2015). In the end, the MBWCS produced substantially higher wheat than the MWCS system.

In a nutshell, maize+blackgram intercropping under MBWCS had significant residual effect on growth, partial factor productivity, resource-use efficiency and productivity of succeeding wheat crop. Thus, wheat cultivation under CA-based ICM_7 practice comprising ZT+PRB + 100% RDF + Sulf+Met at PoE with 4 irrigations (45 mm depth) and need-based IDM/ IPM under MBWCS could result in higher wheat productivity than MWCS.

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