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Prerna Jaiswal
Ph.D. Scholar, Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Sanjay K Dwivedi
Principal Scientist, Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Deeksha Rani Kashyap
M.Sc. (Ag), Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Chanchal Porte
Ph.D. Scholar, Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Corresponding Author:
Prerna Jaiswal
Ph.D. Scholar, Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

Advances in agronomic management of rice-mustard cropping system: A review

Prerna Jaiswal, Sanjay K Dwivedi, Deeksha Rani Kashyap and Chanchal Porte

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Abstract
In India, the rice-based cropping system is a predominant food production system accompanied by rice as the primary food crop. However, the cereal-based cropping system has low productivity besides highly nutrient exhaustive contributing in the declining of soil fertility. Hence, crops that can improve the fertility status *i.e* legumes and oilseeds should be incorporated in the cropping system. The adoption of rice-mustard cropping system plays a vital role in meeting the demand of edible oil while reducing disparity between production and consumption for oilseeds and their import. The *Kharif-Rabi* rotation efficiently utilizes water resources wherein rice, a crop with high water requirement, cultivated during the monsoon and while mustard, a crop with relatively better tolerance to drought, make use of residual soil moisture in winter. This comprehensive review examines the advance agronomic management practices such as rice based cropping systems, importance of rice-mustard cropping system, varietal development, land preparation, seed priming, seed rate, nutrient, irrigation and weed management etc. which influence the productivity and sustainability of rice-mustard cropping system.

Keywords: Rice-based cropping system, rice-mustard cropping system, productivity, edible oil, agronomic management practices

Introduction
Rice is the staple food for more than half of the world's population (IRRI, 2009) [12]. It is a member of the Poaceae family and genus *Oryza*. It is the most significant and extensively cultivated food crop grown extensively in tropical and subtropical regions, which provides half of the daily food for one of every three persons on the earth. About 70% of the global population consumes rice as an essential food while more than two billion people in Asia alone, obtain 60-70% of their energy intake from rice and its products (Kumar *et al.*, 2023) [46]. Rice is grown on 161 million hectares of land with an annual production of about 678.7 million tons of paddy (Statista, 2019) [72]. In India, the total cultivated area under rice (43.8 M ha), production (163.7 MT) and productivity of 2.78 t ha^{-1} (Agriculture Statistics at a Glance, 2018) [4] and is the second highest producer (121.26 MT) contributing 22% of global rice production (FAO, 2018) [22]. India is expected to produce 125 MMT of rice in 2022-2023 from 46 million hectares of planted area, yielding 4.08 MT/hectare of rough rice (USDA 2022) [74]. Chhattisgarh is renowned as the "Rice Bowl of India," boasting a production area of approximately 3.89 million hectares with a productivity of 3.2 t ha^{-1}. In Chhattisgarh, rice based cropping system is vegue where rice is grown on 38.1 lakh ha with a production of 80.4 lakh tones having productivity of 2101 kg ha^{-1}. Paddy cultivation in Chhattisgarh involves both transplanting under puddled fields and direct seeding through seed drills and broadcasting on unpuddled fields, followed by beushening. However, concerns arise during the *Rabi* season regarding the cultivation of second crops after rice, attributed to challenges such as field preparation, proper crop establishment method, shortage of moisture especially at upper soil layer and poor germination. Consequently, the coverage of acreage for second crops is only around 38%, a relatively low figure given the state's natural resources, particularly rainfall. During the *Rabi* season, among pulses chickpea, lathyrus and pea while among oilseeds mustard and linseed are popularly grown in the state (Puhup *et al.*, 2021) [58, 59].

In India, during 2019-20, mustard and rapeseed occupied 6.33 million hectares, producing 6.69 million tons with an efficiency of kg ha^{-1}. And yet we are an oil deficient economy. There is a yawning gap between demand and supply of edible oil. This problem began with India's oil consumption, reaching up to 18 kg per person in recent years from less than 6 kg in 1992-1993. The Directorate of Sugar & Vegetable Oil (DS&VO) provides statistics that support this assessment. The total consumption of edible oils in India increased from 159.54 MMT in 2008-09 to 249.8 MMT in 2018-19, at a compound annual growth rate (CAGR) of 4.6%, according to DS&VO. And herein lies the problem. As contrast to the aforementioned statistics, domestic oil seed production rose somewhat from 27 MMT to 32 MMT over the same period at a CAGR of 1.6% (Singh *et al*., 2022) [69]. In Chhattisgarh, the total area of mustard production was reported to about 1.57 million hectares with productivity of 0.47 t ha^{-1}. Mustard oil fulfills one-third of the nation's edible oil requirements and to address these needs the country highly depends on imports of vegetable oil. Data compiled by the Solvent Extractors' Association of India (SEA) reveals that the import of vegetable oils surged by 26% in July 2019, reaching 14.12 lakh tonnes compared to 11.19 lakh tonnes in July 2018. To mitigate this reliance on imports, there is a crucial need to reduce the importation of vegetable oils by expanding the cultivation of oilseed crops. Enhancing the yields of the mustard crop is particularly vital in achieving this objective (Chaturvedi and Kushwaha, 2022) [13]. Indian agriculture is largely dependent on rice based cropping systems. Elevating the productivity of these systems has proven to be a crucial strategy for attaining livelihood security, increased income, poverty alleviation, and the generation of employment opportunities. The rice-based cropping system plays a pivotal role in securing the livelihoods of over half a billion farm families (Panda *et al*., 2018) [54]. Rice-based cropping system is a major cropping system practised in India, which include the rotation of crops involving cereals, pulses, oilseeds, cotton, sugarcane, green manures, vegetable, etc. Various rice-based cropping systems have been reported from different parts of India ranging from rice-rice-rice to rice followed by different cereals, pulses, oilseeds, vegetables and fibre crops (Deep *et al*., 2018) [20]. Among the rice-based cropping systems, the major ones are rice- wheat (9.8 m ha), rice-rice (5.9 m ha), rice-fallow (4.4 m ha), rice-pulses (4.4 m ha), rice vegetables (1.2 m ha), rice groundnut (1.0 m ha), rice-mustard (0.5 m ha), rice-potato (0.5 m ha) and rice-sugarcane (0.4 m ha) reported by Yadav *et al*., 2013 [77].

Rice based cropping system in India

An estimate says that India is home to more than 250 cropping systems. Based on rationale spread distribution of crops; approximately 30 cropping systems have been identified as important cropping systems. Among these, the predominant cropping system in India is the rice-based cropping system. In rice ecosystem of eastern India, rice-rice, rice-wheat, rice-mustard, rice-groundnut, rice-potato and rice-pulses are commonly practiced cropping sequences (Panda *et al*., 2018) [54]. A significant portion of the country's food grain pool is contributed by the rice-wheat and rice-rice cropping systems, whereas other rice based cropping systems have their significance to contribute the national production of oil-seed and pulse crops (Sharma *et al*., 2014) [65]. Lowland and upland crops can be grown in rice-based cropping systems (Deep *et al*., 2018) [20]. The selection of crops in cropping systems primarily relied on the agro-climatic and socio-economic conditions of the region with rice serving as a main crop (Table 1).

Table 1: Rice-based cropping systems in different agro-climatic regions of India

Agro-climatic region	Rainfall (mm)	Soils	Prominent cropping system
Western Himalayan (Himachal Pradesh, Jammu & Kashmir, Uttarakhand)	1650-2000	Hill and Sub-montane	Rice-wheat, Rice-potato-potato
Eastern Himalayan (Assam, North East states, West Bengal)	1840-3528	Red sandy, Laterite, hill, Alluvial	Rice-fallow, Rice-rice, Rice-pulses/oilseeds
Lower Gangetic Plain (West Bengal)	1302-1607	Alluvial, Red and yellow	Rice-rice, Rice-wheat, Rice-potato-jute/vegetables
Middle Gangetic Plain (Bihar, eastern Uttar Pradesh)	1211-1470	Alluvial, Tarai and Calcareous	Rice-wheat Rice-maize, Rice-potato-sunflower
Upper Gangetic Plain (central and western Uttar Pradesh)	721-979	Alluvial, Tarai	Rice-wheat Sugarcane-ratoon-wheat
Trans Gangetic Plain	360-890	Alluvial and Calcareous	Rice-wheat
Eastern plateau and Hills (Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra)	1296-1436	Red, Yellow Laterite	Rice-blackgram Rice-niger/linseed Rice-Vegetables
East coast Plain and Hills (Andhra Pradesh, Odisha, Tamil Nadu, Puducherry)	780-1287	Deltaic alluvium, Red, Laterite	Rice-groundnut-greengram, Rice greengram/blackgram, Rice-rice
West coast Plains and Hills (Goa, Maharashtra, Karnataka, Kerala, Tamil Nadu)	2226-3640	Coastal alluvium, Red, Laterite	Rice-rice
Andaman and Nicobar Island	1600-3000	Red	Rice-fallow

(Gill *et al*., 2008) [26]

Importance of mustard in rice based cropping system

Mustard (*Brassica juncea* L.) is cultivated during the dry winter season and features a deep taproot system, reducing its dependence on irrigation water. Its irrigation water requirement is significantly lower (~150−200 mm) compared to wheat (400−500 mm) thus, can lead to save water and enhance water-use efficiency. The Government of India assured minimum support price (MSP) for mustard which gets revised every year (GOI, 2018-19). In 2018-19, the MSP of mustard has substantially increased to INR 42,000 t^{-1}, which is almost 2.3 times higher the MSP of wheat ~INR 18,400 t^{-1}). Mustard can be an economically alternative crop to wheat in both irrigated and rainfed agro-ecologies. Recently, the Government of India (GOI) has adopted a policy to promote mustard in rice fallow areas, widely distributed in the rainfed agro-ecosystems of eastern, central and peninsular India and North-eastern Hill Region. India accounts for 79% (~11.65 million ha) of the total rice fallows of South-Asia (~15.0 million ha) (NAAS, 2013) [51]. In fact, CA with ZT and residue retention suits better for growing mustard after rice in rainfed conditions (Singh *et al*., 2018) [67, 70].

Rice and mustard ecosystem

In India, rice is cultivated under highly diverse conditions with area stretching from 79° to 90° E longitude and 16° to 28° N latitude under varying agro-ecological zones. Primarily grown during the wet season, rice cultivation faces the challenge of unpredictable rainfall distribution. Furthermore, rice is cultivated in areas, where water depth reaches 2-3 m or more. Rice cultivated in Kuttanad district of Kerala below the sea level, whereas in the state of Jammu and Kashmir, it is cultivated upto an altitude of 2000 m above sea level; with temperature range of 15-40°C and average annual rainfall range from 30 mm in Rajasthan to more than 2800 mm in Assam. Rice is primarily grown under four major ecosystems broadly classified as (i) irrigated, (ii) rainfed lowland, (iii) rainfed upland and (iv) flood prone. In lowland ecosystems rice seedlings are transplanted in puddled condition and the fields are maintained either in continuous submergence or intermittently flooded depending on soil texture, rainfall and availability of irrigation water. In the case of upland rice the seeds are directly sown on pulverized seedbed and fields are never flooded. (Pathak *et al*., 2011) [53].

Mustard is primarily cultivated in temperate climates, although it is also found in specific tropical and subtropical regions as a cold-weather crop. Indian mustard exhibits tolerance to annual precipitation of 500 to 4200 mm, annual temperature of 6 to 27◦C, and pH of 4.3 to 8.3. Rapeseed-mustard follows C3 pathway for carbon assimilation. Therefore, it has efficient photosynthetic response at 15-20 °C temperature. The plant reaches its maximal CO_2 exchange range at this temperature, after which it begins to decline. *Rai* is predominanatly grown as a rainfed crop, moderately tolerant to soil acidity, preferring a pH from 5.5 to 6.8, thrives in areas with hot days and cool night and can fairly sustain drought. Mustard requires well drained sandy loam soil. Rapeseed-mustard has a low water requirement (240-400 mm) which fits well in the rainfed cropping systems. Nearly 20% area under these crops is rainfed (Shekhawat *et al*., 2012) [66].

Methods of rice establishment

Direct-seeded rice (DSR) can be implemented through three methods, namely, (1) dry seeding, (2) wet seeding and (3) water seeding by avoiding the nursery and transplantation (Joshi *et al*., 2013) [37]. In dry seeding, seeds are sown directly into dry soil at a depth of 2-3 cm, immediately after the pre-monsoon showers. This method is suitable for a rain-fed and irrigated environment with precise water control. Wet seeding involves broadcasting or sowing pre-germinated seeds in puddled soils, making it highly suitable for rain-fed lowlands and irrigated areas with good drainage facilities. This method is commonly practiced in countries such as Malaysia, Thailand, Vietnam, the Philippines, and Sri Lanka (Pandey & Velasco, 2005) [55]. Jaiswal *et al*. (2020) [36] concluded that growth parameters and yield attributes were maximum under transplanting of 20 days old seedling among different rice establishment methods which was at par with line sowing of normal seeds. Drum seeded rice is recommended in India using the wet method, where seeds are sown in line on the puddled soil. In the water seeding method, seeds are broadcast in standing water (5-10 cm) in areas where red rice or weedy rice problem exists. Satyaraj Guru (2022) [63,64] witnessed that conventional tillage-vattar-DSR through multi-crop planter fitted with inclined plate seed metering mechanism [CT-DSR(V)-MCP] treatment registered highest value of growth parameters, yield and yield attributing characters which was found at par with conventional tillage-vattar-DSR seed-cum-fertilizer drill fitted with fluted roller seed metering mechanism [CT-DSR(V)-SCFD] and conventional tillage-dry-DSR through seed-cum-fertilizer drill fitted with fluted roller seed metering mechanism [CT-DSR(D)-SCFD] among different methods of establishment on pooled basis (*Kharif* 2021 and 2022), represented in Table 2.

Table 2: Yield attributes and yield of direct seeded rice as influenced by different establishment methods on pooled basis (*kharif* 2020 and 2021)

Treatments		Number of effective tillers (no.m^{-2})	Panicle length (cm)	Panicle weight (g)	Grain yield (t ha^{-1})
T_1	CT-DSR(V)-MCP	434	24.0	4.84	6.31
T_2	CT-DSR(D)-MCP	403	23.9	4.05	5.87
T_3	CT-DSR(V)-SCFD	413	24.0	4.19	6.05
T_4	CT-DSR(D)-SCFD	396	22.7	3.70	5.47
T_5	CT-DSR(B)	376	22.6	3.49	5.16
T_6	CT-(B fb B)	362	22.2	3.34	4.86
SEm±		10.83	0.24	0.08	0.19
CD (P=0.05)		31.28	0.68	0.22	0.55

CT-DSR(V)-MCP: Conventional tillage-vattar-DSR through multi-crop planter fitted with inclined plate seed metering mechanism; CT-DSR(D)-MCP: Conventional tillage-dry-DSR through multi-crop planter with inclined plate seed metering mechanism; CT-DSR(V)-SCFD: Conventional tillage-vattar-DSR through seed-cum-fertilizer drill fitted with fluted roller seed metering mechanism; CT-DSR(D)-SCFD: Conventional tillage-dry-DSR through seed-cum-fertilizer drill fitted with fluted roller seed metering mechanism; CT-DSR(B): Conventional tillage-manual broadcast seeding; CT-(B *fb* B): Conventional tillage - manual broadcast seeding with *Biasi*
(Satyaraj Guru, 2022) [63, 64]

Varietals Development

The selection of cultivars based on an ideal type has significantly contributed to increased rice yield. Rice cultivars with fewer tillers, lower panicle weights with thick roots and culms are suitable for DSR (Won *et al*., 1998) [76]. For dry-seeded rice, early heading rice varieties with better drought tolerance, such as IR36 with 105 day duration, have demonstrated favorable performance (Mackill *et al*., 1996) [49]. At IRRI, early heading type of a popular variety IR64 is being developed to provide suitable breeding materials for water saving rice cultivation (Fujita *et al*., 2007) [23]. In India, released varieties like CSRC(S) 7-1-4 and CSR89-IR8 (CSR43) suitable for inland salinity and Luna Sampad (CR Dhan 402), Luna Suvarna (CR Dhan 403) and Luna Sankhi (CR Dhan 405) are suitable for coastal salinity. India released one drought tolerant variety named Shabhagi dhan (Gregorio *et al*., 2013) [28].

Varieties released by IGKV Raipur includes, Scented: Indira sugandhit dhan, Badsaha bhog selection-1, Dubraj selection-1, Biofortified: CG zinc rice-1, CG madhuraj dhan-55, Zinco rice SS and Drought tolerant: Indira aerobic-1, Indira barani dhan-1, CG barani dhan-2.

The first Indian mustard hybrid, named NRCHB-506, has been developed at Directorate of Rapeseed-Mustard Research, Bharatpur which can catapult the output of the country's key oil crop. Other high yielding varieties include JM-1, JM-3, Pusa Bold, NRCDR-2 and NRCDR 601. Their yield potentials vary from 16 to 25 q ha^{-1}. At IARI, an early-maturing and bold seeded mustard variety has been developed called Mehak (Chauhan *et al*., 2006) [14]. Pusa Jaikisan of *B. juncea* is the first variety though tissue culture. For nontraditional areas, Indian mustard varieties Rajat, Pusa Jaikisan and Sej.2 have been recommended. DRMR 150-35 variety recommended for zone V (Bihar, West Bengal, Chhattisgarh etc,) released at Directorate of Rapeseed-Mustard Research. Chhattisgarh sarso-1 (110-115 days) and C.G. toria-1 were released varieties from Indira Gandhi Krishi Vishwavidyalaya (IGKV) Raipur.

Land preparation

This is a pre-requisite for good crop husbandry. During the summer, weed management is aided by plowing the fields. In the context of Direct-Seeded Rice (DSR) technology, precision land leveling has proven beneficial for better germination, controlling weeds emergence, uniform irrigation saving considerable amount of water and increasing water use efficiency with ultimate increase in grain yield (Pathak *et al*., 2011) [53]. Two cross ploughings are essential to attain good tilth of soil and weed free land. Excessive tillage should be avoided. Before sowing, it is recommended to place 50% nitrogen (N) fertilizer and the full dose of phosphorus and potash in the furrow. Organic manures such as farm yard manure or composts should be applied approximately 15 days before transplanting and mixed with the soil during ploughing (Das *et al*., 2012) [16]. Land levelling is the foremost crucial step for adaptation of DSR. Before direct sowing of rice land should be leveled through Laser land leveller. Laser land levelling technology renders a great potential for uniform crop establishment, uniform distribution of irrigation, water saving, improve nutrient use efficiency, better environmental quality and higher grain yields (Kakraliya *et al*., 2016) [38].

A mustard seedbed should be firm, moist and uniform which allows good seed-to-soil contact, even planting depth and quick moisture absorption leading to a uniform germination. Crop growth and grain yield both are affected by tillage. The different tillage systems are as follows: conventional tillage involves moldboard ploughing followed by disc harrowing; reduced tillage comprises of disc ploughing accompanied by disc harrowing and complete zero tillage includes sowing of crops under uncultivated soil. Minimum tillage, with or without straw, strengthen soil moisture conservation and moisture availability throughout the crop growth, leading to increased root mass, yield components and seed yield (Asoodari *et al*., 2001) [7]. In mustard, zero tillage is preferred as it conserves more moisture in the soil profile during early growth period (Rathore *et al*., 1999) [60].

Seed priming

Seed treatment is a vital step in ensuring healthy plant growth. It should be done with, common salt or Carbendazim 12% + mancozeb 63% WP, Streptocyclin or Emisan (Methoxy ethyl mercury chloride). To manage soil borne diseases, seeds must be treated with the recommended fungicide. For this weighed quantity of seeds are soaked in fungicide (10 g bavistin + 1g streptocyclin in 10 litre water solution for 10 kg seed) solution for 24 hours. Amount of water used for soaking is similar to quantity of seed used for seed treatment. After 24 hours, seeds are removed from fungicide solution and dried in shade for 1-2 hours prior to sowing, ensuring they achieve a friable texture (Kakraliya *et al*., 2016) [38].

Seed priming through controlled hydration and dehydration amplifies early germination of mustard seed in less time, even in compacted soil (Snapp *et al*., 2008) [71]. In order to intensify the seed germination, seed priming *i.e*., seeds soaking overnight in water, thereafter dried in shades before sowing. Seed treatment should be done with bavistin at 2.5 g kg^{-1} to prevent the seed-borne diseases (Pathak *et al*., 2011) [53]. The soaking of mustard seeds in 0.025% aqueous pyridoxine hydrochloride solution for 4 hours improved germination. The combination of pyridoxine + $N_{60}P_{20}$ + $N_{15}P_5$ (top dressing) accelerated the crop performance by increasing seed yield and oil yield by 15.8 and 13.5%, respectively, over the control (Khan and Aziz, 1993) [43]. The differential response of varieties for imbibition gives advantage to some of them to germinate early as compared to others.

Seed rate

Seed rate @ 20-30 kg ha^{-1} (with inclined-plate seeding mechanism) and 35-45 kg ha^{-1} (with fluted-roller seeding mechanism) with seeding depth: 1-2 cm is optimal for DSR (IRRI, 2013) [34]. Use of planters having inclined plate devices or a cupped metering system is very useful for proper spacing (20 cm) and reducing seed rate (Pathak *et al*., 2011) [53]. The seed rate of 60-80 kg ha^{-1} (broadcasting) and 80-100 kg ha^{-1} (drilling) for dry direct seeding while 80-100 kg ha^{-1} (broadcasting) and 80 kg ha^{-1} (drum seeding) for wet direct seeding is recommended (IRRI, 2018) [35].

It is advisable to avoid continuous cultivation of the same field for the production of high-quality seeds. In mustard, the recommended spacing is 30 x 10 cm for varieties and 45 x 10 cm for hybrids. Sowing of 4-5 kilogram seed in rows of 45 cm at a depth of 2.5 to 3.0 centimeter. For mixed cropping, sowing of 1.5 to 2 kg seed per hectare is adequate. Sowing could be done either behind the plough or through seed drill. Prior to sowing, seed should be treated with thiram or captan @ 2.5 g kg^{-1} seed (Bhanu *et al*., 2019) [9]. Seed rate of 4-5 kg ha^{-1} along with row spacing of 45 was recommended for mustard.

Time of sowing

In order to achieve the success in DSR crop, time of sowing is crucial in the main rice growing season (*Kharif*). Sowing of crops should be completed at10-15 days before onset of monsoon. The crop should establish 2-3 leaves before rain starts. This would allow the early root establishment so that crop could compete easily with emerging weeds besides permitting timely sowing of succeeding wheat crop (Pathak *et al*., 2011) [53]. Sowing should be completed within second fortnight of June for upland direct sown crops in mid altitude condition. Timely sowing is requisite to have adequate time for the succeeding *Rabi* crops, which are generally sown in the second fortnight of October while in lowland it should be done in the third week of April (Das *et al*., 2012) [16].

Sowing time is the most essential nonmonetary input to accomplish target yields in mustard. Soil temperature and moisture have effect on sowing time of rapeseed-mustard in various territories of the country. However different cultivars have a distinctive response to date of sowing, mustard sown on

14 and 21 October took significantly much longer days to 50% flowering (55 and 57) and maturity (154 and 156) contrast to October 7 planting (Kumar *et al*., 2001) [44]. Low yield, oil content and poor growth were the outcomes of delayed seeding (AICRP-RM, 1998) [1]. The date of sowing affects both insect-pest and disease incidence. The least incidence of *Sclerotinia* was observed when sown on October 21. The maximum (20.5-25.4 °C) and minimum (3.9-10.7 °C) temperatures during flowering of crops established through sowing on October 21 were negatively correlated with the development of *Sclerotina* stem rot. The sowing time for mustard was 15 October to 15 November.

Nutrient management

Fertilizer recommendation for DSR is similar as that of puddled transplanted rice. Although, it is preferable to apply 10-15 kg additional N in DSR than puddled transplanted rice (Kakraliya *et al*., 2016) [38]. Nutritional requirement should be addressed on the basis of soil analysis of the crop field. The following fertilizer schedule should be applied in absence of soil analysis. Blanket application of 120-150 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1} may be provided along with 25 kg $ZnSO_4$ ha^{-1}. In light textured soil, ¼ N and total of P_2O_5 and K_2O should be applied basally. During maximum tillering and panicle initiation stage, the remaining amount of N should be applied as top dressing into two splits (Pathak *et al*., 2011) [53]. Farmers observe the color of rice leaves at regular intervals of 7-10 days in the real-time option from early tillering (20 DAS) in addition N is applied whenever the colour is below a critical threshold value (IRRI, 2010) [33]. Puhup (2021) [58, 59] noticed that among the tillage and nutrient management approaches, the growth parameters and yield attributes were highest under conventional tillage (CT)-transplanted rice (TPR) with 100% RDF + 2 t FYM, which was comparable to CT-TPR with 100% RDF and CT-DSR with 100% RDF + 2 t FYM.

The seed and oil yields were increased by improving the setting pattern of siliquae on branches, number of siliquae plant^{-1} and other yield attributes when nutrient is supplied adequately (Chitale and Bhambri 2001) [15]. Crop cultivated with zero tillage is also more productive (695 kg ha^{-1}) with 80 kg N ha^{-1} (AICRP-RM, 2007) [2]. Phosphorus applications up to 60 kg ha^{-1} greatly increased dry matter plant^{-1}. Rapeseed-mustard has highest sulfur demand of all the oilseed crops. With irrigation, sulfur enhanced mustard yields by 12 to 48% and with rainfed conditions, it increased yields by 17 to 124% (Shekhawat *et al.*, 2012) [66]. The recommended dose of nutrient for mustard was 100:60:40 Kg ha^{-1} NPK for better yield. Singh *et al*. (2018) [67, 70] found that for significant growth and yield attributes, integrated nutrients management using RDF + Vermicompost 3 t ha^{-1} + FYM 5 t ha^{-1} + Azotobacter + PSB produces the best results. Plant nutrient management through STCR approach showed better response to added nutrients. The yield of mustard enhanced with increasing additional nutrient (Dhruw *et al*., 2018) [21]. Thaneshwar *et al.* (2017) [73] revealed that the significantly better growth attributes, yield attributes and grain yield (22.75 q ha^{-1}) was obtained with combined application of RDF + vermicompost @ 5.0 t ha^{-1} over rest of the treatments. The minimum grain yield (19.15 q ha^{-1}) was received in treatment RDF (120:60:40:30 Kg ha^{-1} NPKS).

Irrigation management

The water-use efficiency of rice is much lower compared to other crops. On an average, 2500 litres of water is used, ranging from 800 litres to more than 5000 litres to produce 1 kg of rough rice (Bouman, 2009) [32]. In Asia, the average amount of water required for irrigated rice is between 1300 and 1500 mm. An estimated 34−43% of the total world's irrigation water, or around 24−30% of the entire world's developed fresh water resources received by irrigated rice (IRRI, 2018) [35]. Farmers commonly establish DSR crop with pre-sowing irrigation in heavy textured soils. Irrigation can be delayed from 7-15 days at first post sowing with subsequent irrigations at an interval of 5-10 days. During critical stages of seedling emergence, active tillering, panicle initiation and flowering, water stress must be avoided (Kaur and Singh, 2017) [41]. In some studies the DSR crop saved 32% water than transplanted rice without any yield penalty. In conventional rice production, 3000 to 5000 L of water are required to produce 1 kg of rice.

The crop rapeseed-mustard is susceptible to water scarcity. The water requirement for mustard cultivation usually varies between 300 to 400 mm year^{-1}. The IW/CPE ratio of 0.6 is optimum for the water use efficiency. In rainfed conditions, mustard seed yield increased up to 28% with required two irrigations, one at flowering stage and another at siliqua formation stage. Two irrigations given at pre-flowering and pod-filling stages increases seed yield by 33% compared to unirrigated crops. However, irrigation subjected to vegetative and pod formation stages impart highest advantage. Consequently, two irrigations one at 30-35 days after sowing and second at 55 to 60 days after sowing must be provided to the mustard crop. The dry matter yield decreases excessively with saline water (12 and 16 dS m^{-1}) if applied during pre-sowing or afterward. Application of saline irrigation at the pre-flowering stage or later on leads to decrease grain yield by means of 50% and 70%, respectively (Bhanu *et al*., 2019) [9].

Weed management

Effective weed control is crucial for DSR. Weed pressure can be reduced through adoption of cultural methods of weed control such as stale seed bed technique, use of surface mulch, cover crops (*viz*., *Sesbania rostrata*, *Phaseolus radiatus* and *Vigna unguiculata*) and brown manuring. treatment with pendimethalin (0.75 kg ha^{-1}) should be applied as pre-emergence followed by post emergence application (15-25 days after sowing) of bispyribac (0.025 kg ha^{-1}) for controlling as sedges, grasses along with broadleaf, azimsulfuron (0.020 kg ha^{-1}) for controlling broadleaf and sedges including *Cyperus rotundus* and Fenoxaprop+ safener (0.067-0.083 kg ha^{-1}) for successfully controlling grasses except *Echinochloa* sp. (Kaur and Singh, 2017) [41].

Satyaraj Guru *et al*. (2022) [63, 64] revealed that among the integrated weed management practices, at 30 DAS the maximum and minimum weed control efficiency was recorded under the oxadiargyl 80 WP @ 80g *a.i.* ha^{-1} PE *fb* one HW at 25 DAS and trifamone 20% + ethoxysulfuron 10 WG (Pre-mix) @ 67.5g *a.i.* ha^{-1} (Council active) at 15 DAS + One spot hand weeding at 40 DAS treatment, respectively on mean basis. At 45 DAS, the maximum weed control efficiency was noticed under the oxadiargyl 80 WP @ 80g *a.i.* ha^{-1} PE *fb* two HW at 20 & 40 DAS treatment on mean basis. At 90 DAS, the oxadiargyl 80 WP @ 80g *a.i.* ha^{-1} PE *fb* two HW at 20 & 40 DAS and weed free (20, 40 & 60 DAS) treatments exhibited more than 90% weed control efficiency. Whereas, the oxadiargyl 80 WP @ 80g *a.i.* ha^{-1} PE *fb* fenoxaprop-P-ethyl (6.7%) @ 60 *a.i.* ha^{-1} (Ricestar) + ethoxysulfuron (15% WDG) @ 15g *a.i.* ha^{-1} as EPoE (Sunrise) at 20 DAS (at 2-5 leaf stage of weed) treatments recorded the lowest weed control efficiency at 45 and 90 DAS on mean basis (Table 3). The integrated approach of chemical+manual weeding noticed highest growth and yield within the integrated weed management practices.

A concerning 15-30% reduction in crop yield as well as complete failure in the case of rapeseed-mustard is caused by weeds. The critical period is of 15-40 days. Crop plants compete with weeds for light, water, space as well as nutrients. Hence, timely and appropriate weed control considerably increases the crop yield and thus nutrient use efficiency (Shekhawat *et al*., 2012) [66]. Application of pendimethalin 1.0 kg *a.i.* ha^{-1} as pre-emergence (PE) observed significantly higher seed yield and post emergence (PoE) application of fluazifop-p-butyl 0.125 kg *a.i.* ha^{-1} at 25-30 DAS found effective and recorded highest seed yield (2510 kg ha^{-1}) which was higher by 24% over the weedy check although, the weed control efficiency (WCE) was maximum with the pendimethalin 1.0 kg *a.i.* ha^{-1} (AICRP-RM, 2023) [3].

Table 3: Weed control efficiency (WCE) at different time intervals as influenced by different weed management practices in direct seeded rice pooled basis (*kharif* 2020 and 2021)

Treatments		WCE (%)			Grain yield (t ha^{-1})
		30 DAS	45 DAS	90 DAS	
T_1	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb one HW at 25 DAS	98.9	93.5	87.1	5.55
T_2	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb one mechanical weeding at 20 DAS	91.2	81.1	74.5	5.12
T_3	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb Two HW at 20 & 40 DAS	96.3	99.7	91.3	5.87
T_4	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb one mechanical weeding at 20 DAS fb one hand weeding at 40 DAS	91.9	99.5	89.1	5.82
T_5	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb Bispyribac-Na @ 25g a.i./ha (Nominee Gold) at 20 DAS (at 2-5 leaf stage of weed)	95.1	92.9	83.4	5.56
T_6	Oxadiargyl 80 WP@ 80 g a.i./ha PE fb Premix Penoxsulam (1.02%) + Cyhalofop-butyl (5.1%) (P+C, 6.12%) @ 0.135 kg/ha EPoE as ready-mix (Vivaya) at 20 DAS (at 2-5 leaf stage of weed)	94.9	91.7	82.6	5.48
T_7	Oxadiargyl 80 WP@80g a.i./ha PE fb Fenoxaprop-P-Ethyl (6.7%) @ 60 g a.i./ha (Ricestar) + Ethoxysulfuron (15% WDG) @ 15 g a.i./ha as EPoE (Sunrise) at 20 DAS (at 2-5 leaf stage of weed)	94.2	79.8	50.5	4.68
T_8	Oxadiargyl 80 WP@ 80g a.i./ha PE fb Premix Florpyrauxifen-Benzyl + Cyhalofop Butyl (Novelect) at 20 DAS (at 2-5 leaf stage of weed)	94.5	83.6	72.0	5.09
T_9	Trifamone 20% + Ethoxysulfuron 10 WG (Pre-mix) @ 67.5g a.i./ha (Council active) at 15 DAS + One spot hand weeding at 40 DAS	58.1	85.4	62.4	4.97
T_{10}	Premix Florpyrauxifen-Benzyl + Cyhalofop Butyl (Novelect) at 15 DAS (at 2-5 leaf stage of weed)+ One spot hand weeding at 40 DAS	68.7	84.0	55.2	4.86
T_{11}	Motorized weeder twice (single/double row type) at 15 and 35 DAS	88.3	87.3	61.8	4.90
T_{12}	Motorized weeder twice (single/double row type) + Intrarow hand weeding at 15 and 35 DAS	92.9	95.3	87.7	5.64
T_{13}	Weed Free (20, 40 and 60 DAS)	97.2	99.7	95.1	6.00

(Satyaraj Guru *et al*., 2022) [63, 64]

Insect pest management

Although over 100 insect species are regarded as pests in rice production systems worldwide, only around 20 of those species cause remarkable economic damage (IRRI, 2018) [35]. The stem borer, *gundhi* bug, leaf folder, root aphid etc. are the major insect pest of rice. Spraying Monocrotophos 36 EC @ 2 ml litre^{-1} or Chlorpyriphos 20 EC @ 1 ml litre^{-1} of water at 45 DAT is an efficient way to manage insect pests in rice, including leaf folders, case worms, stem borer, and hispa. Gundi bug management involves dusting with Fenvalerate 0.4% @ 20-25 kg ha^{-1}. Termites and white grubs are controlled in upland environments by treating seeds with 0.75 kg *a.i.* 100 kg seed^{-1} or applying 3g of carbofuran @ 1 kg *a.i.* ha^{-1}. Using disease-free and healthy seed also protects the plants against insect pest and diseases. Growing multiple varieties (maintain diversity) is a good option to avoid complete crop failure owing to pest/disease problem within a particular variety (Das *et al*., 2012) [16].

Around 50 insects are well known to damage *Brassica* crops. Mustard aphids, saw fly, painted bug etc. are the major pests of mustard crop. Aphids are capable of causing yield losses up to 97% while sawfly and painted can cause losses up to 15% and 30%, respectively. In most part of the country January - February is the peak period for activity of aphids (Kumar *et al*., 2008) [45]. Two-three sprayings of insecticides *viz*., Chlorpyrifos 20% EC @ 200 ml or Oxydemeton-methyl 25% EC @ 400 ml in 200-400 L of water acre^{-1} at 10-15 days interval to control aphids. For controlling mustard saw fly, spray Dimethoate 30% EC @ 264 ml or Quinalphos 25% EC @ 480 ml or Malathion EC 50% EC @ 600 ml in 200-400 L of water acre^{-1}. Application of Phorate 10% CG @ 6000 g acre^{-1} for control of painted bug (Bhanu *et al*., 2019) [9].

Disease management

Cereal cyst nematodes prone to be an issue on lighter soils, especially during drier years. Appearance of small patches of stunted growth, reduced tillering and pale green-yellowish plants are the initial symptoms of cyst nematodes. The problem is likely to be aggravated by ongoing non flooded DSR in the similar field. It is preferable to avoid DSR in fields where nematode problems start to appear (IRRI, 2013) [34]. Important rice diseases include blast, sheath blight, bacterial leaf blight, brown spot, and sheath rot. Seed treatment with Bavistin 50 WP @ 2.5 g kg^{-1} seed protects the crop from blast in nursery and further up to 25-30 days after transplanting. For management of blast and brown spot treat the seeds with Dithane M-45 @ 5 g kg^{-1} seed besides spray the crop with Tricyclazole 75 WP (0.6 g litre^{-1}) (Das *et al*., 2012) [16].

About 19.9% of oilseed crop losses are attributable to biotic stresses, with diseases being the primary cause of significant yield decline at various growth stages. Treatment of seeds with biocontrol agents *viz*., *T. viride*, *G. virens* or botanicals like *Allium sativum* bulb extract (1% w/v) or carbendazim @ 0.1% *a.i.* or mixture of carbendazim with Apron 35 SD (6 g kg^{-1}) (Kumar *et al*., 2008) [45]. Crop should be sprayed 3-4 times with Dithane M-45 (0.2%) or Difolatan (0.2%) at 10-15 days when favorable environmental conditions persist for the disease for

Alternaria blight. For the control of powdery mildew, spray Sulfex (0.2%) or Karathane (0.1%) (Bhanu *et al*., 2019) [9].

Harvesting

Harvesting time should be around 110-120 days after sowing for direct seeded rice, depending upon the variety's growth duration. Normally the ideal harvest time for late-maturing varieties lies between 130 and 136 days after sowing, 113 and 125 for medium duration and 110 days for early-maturing varieties. The best time to harvest during the dry season is 28-35 days after heading, or when the panicle tip emerges from the leaf sheath. Harvesting during the wet season is best done 32-38 days after heading. The optimal range for grain moisture content is 20 and 25% (wet basis). Grains should be firm but not brittle when squeezed between the teeth. Harvest at minimal surface moisture (e.g. from previous rainfall or early morning dew). When 80−85% of the grains are straw colored (i.e., yellow-colored), harvesting should be done (IRRI, 2018) [35].

Brassicas are an oilseed crop generally vulnerable to shattering. It is more in case of toria cultivars than mustard varieties. Harvesting the crop as soon as it achieves physiological maturity *i.e.* when 75% siliquae of the plant turns yellowish is recommended. Preferably, this should be done in the morning when the siliquae are still damp from dew. After that the harvested plants should be kept for drying in sun for 3-4 days. After the seeds have been cleaned and winnowed, they should be sun-dried for a further three to four days, or until the moisture level reaches 8%. Seed retains its viability for the next crop season and is also quite safe for its storage at this stage. At this point, seed is safe to store and maintains its viability for the upcoming crop season. When drying mustard seeds, it is important to keep the temperature below 52°C to prevent harm to endogenous enzymes. This would hinder the hydrolysis of glucosinolate to isothiocyanate during processing, which is the hot principle (Bhanu *et al*., 2019) [9].

Yield attributes and yield

DSR is a labor and cost-saving technology that can produce yields that are comparable to or even greater yields of DSR can be secured with good management practices (Hayashi *et al*., 2007) [30]. The higher grain yield of DSR in contrast to PTR was acquired mainly because of higher panicle number, higher test weight and lower sterility% (Sarkar *et al*., 2003). Singh *et al*. (2008) [68] noticed that, when compared with transplanted rice, the panicle length was considerably increased under drilling method. Parameswari *et al.* (2014) [57] recorded that, yield of rice in aerobic environment 2.4-4.4 t ha^{-1} which, was 14-40% lower than the flooded environment. Lal *et al.* (2013) [48] revealed significantly higher grain yield (3.98 t ha^{-1}) accompanied by drum seeding (3.37 t ha^{-1}), broadcast seeding (3.27 t ha^{-1}) of sprouted seeds and row seeding (2.95 t ha^{-1}). The highest grain yield (53.59 q ha^{-1}) and straw yield (80.36 q ha^{-1}) were obtained with STCR fertilizer recommendations for 60 q ha^{-1} targeted yield (Pandu *et al*., 2022) [56].

Yield of mustard in irrigated and rainfed condition was about 2.0-2.5 and 0.8-1.0 t ha^{-1} respectively. Kalita *et al.* (2023) [39] revealed that seed, stover and oil yield of Indian mustard were increased in the year round minimum tillage with rice residue retention by 35.97, 23.41 and 38.90%, respectively owing to higher growth and yield attributes than conventional tillage. Keerthi *et al.* (2017) [42] observed that October 15 sown crop resulted in considerably higher total plant biomass and it's partitioning at different growth stages, yield attributes, yields and oil content. Delaying the sowing dates from October 15 to November 15 decreased seed yield by 39.3%. Integrated nutrition management system has a considerable impact on mustard seed and stover yield. Maximum increment in seed and stover yield was recorded in treatment of RDF 100% + FYM 5 t ha^{-1}+ Vermi-compost 2.5 t ha^{-1} +Azotobacter accompanied by RDF 100% + FYM 5 t ha^{-1}+ Vermi-compost 2.5 t ha^{-1}. The lower seed and stover yield were obtained with the treatment RDF 50%. RDF 50% could not fulfilled the nutrient requirement of plant for their growth and production (Singh *et al*., 2022) [69].

Effect of rice on succeeding crops

Direct sowing creates a favorable environment for subsequent crops by preserving the soil structure, which would otherwise be destroyed by continuous puddling. Gangwar *et al*., 2000 [25] studied the impact of rice crop establishment techniques on rice-based cropping systems productivity and profitability, which showed that the productivity of the DSR-wheat, DSR-chickpea, and DSR-mustard systems was higher (14.96 t, 14.48 t, and 13.48 t ha^{-1}, respectively) than that of the PTR-based cropping system (13.53 t, 12.12 t & 11.81 t ha^{-1}, respectively). Mishra and Chaudhary (2010) [50] noticed the maximum yield of mustard seeds (1259 kg ha^{-1}) with application of recommended fertilizer dose along with 10 t compost on preceding rice. Mustard cultivated with recommended fertilizer dose obtained a maximum mean seed yield of 1384 kg ha^{-1}. Seed yield and yield attributes of succeeding mustard shows positive effect of these treatments. Mustard taken after fertilized rice with RDF recorded maximum BC ratio of 2.0. When mustard was grown with 100% RDF the better BC ratio 3.45 was observed. Pooled data of 10 years under rice-mustard cropping system revealed that application of 150% NPK recorded maximum mustard seed yield which was higher by 267% and 20% over control and 100% NPK, respectively (AICRP-RM, 2023) [3].

Conservation agriculture in rice-mustard cropping system

Conservation Agriculture (CA) is regarded to be a feasible option for sustainable intensification of crops in cropping systems and profitable production (Ladha *et al*., 2009; Das *et al*., 2014) [47, 17]. Fundamentally, system-based CA practices and location-specific appropriate crop rotations need to be developed to acquire maximum profit (Das *et al*., 2018; Kassam *et al*., 2018) [19, 40]. This necessitates enough on-stations as well as on-farms researches to be conducted to evolve location-specific appropriate CA practice (Bhattacharyya *et al*., 2013, 2015) [10, 11]. Some of the CA-based component options, like crop residue retention, crop diversification, and zero tillage (ZT), have been assessed in the IGP as alternatives to the traditional tillage method (Saad *et al*., 2016; Hazra *et al*., 2018) [61, 31]. One of the main objectives of implementing CA techniques is to increase soil organic carbon (SOC). Actually, under CA, SOC stability and sequestration are greatly influenced by the quantity and quality of additional crop residues (Weil *et al*., 2003; Gal *et al*., 2007) [75, 24]. Reduced tillage intensity and higher residue addition in a cropping system throughout the year helps to maintain or even raise the SOC level over time. Additionally, brown manuring (BM) is thought to be a climate-resilient technique (Oyeogbe *et al*., 2017) [52], which renders a number of benefits such as weed suppression, moisture conservation, sequestration of carbon and nitrogen, and improvement of soil health.

Das *et al*. (2020) [18] observed that compared to zero till direct-seeded rice (ZTDSR)-ZT mustard (ZTM) system with or without crop residue, the traditional transplanting puddled rice (TPR)-conventional till mustard (CTM) (~TPR-CTM) rotation produced a considerably greater rice grain yield in each of the five years. In contrast, it was inferior to it in the fourth and fifth years, but in this regard, the CA-based ZT rice, mustard, and SMB (summer mungbean) with residue [ZTDSR-ZTM-ZTSMB (+R)] was equivalent with it during the first three years. The five-year mean rice yield in the ZTDSR-ZTM-ZTSMB (+R) system was 10.9% less than in the TPRCTM system overall. With the exception of the first year, this CA-based system produced noticeably greater mustard grain yields every year. The 5 year mean mustard yield was also 33% higher than that of the TPR-CTM. In comparison to the traditional TPR-CTM system, this rice-mustard system based on CA produced noticeably greater very labile (~50.6%) and labile (~47.7%) carbon concentrations at 0-5 cm depth of soil. Since the CA system being productive, profitable and resource-efficient can be recommended.

Conclusion

Agroecological intensification of rice based cropping system primarily aims at accomplishing maximum system productivity along with minimum environmental impact while managing and organizing crops in a manner that they best utilize the available resources (soil, air, sunlight, water, labour, equipments) and beneficial interactions between themselves. Management techniques are needed to bridge the gap and meet the ever-growing demand of oil in the country. In accordance with agro-ecological situations, market and domestic necessities and facilities available with farmers, rice-rapeseed/mustard followed. In order to secure the livelihoods of the nation's poor, small, and marginal farmers, cropping system research methodically concentrated on the development and management of site-specific, acceptable rice-mustard cropping systems. The idea of ecological intensification is to produce more food with a given amount of land, time and other consumable resource. Therefore, we must utilize the food production system through ecological intensification of appropriate rice-based cropping systems in order to improve profitability, address biodiversity protection, mitigate the effects of climate change, and ensure long-term sustainability. For India, to achieve self-sufficiency in edible oils is possible if the production potential of rice-mustard cropping system are exploit through improved technologies and their timely transfer to the cultivators.

Future Line of Research

The acceptance and implementation of any technology in contemporary agriculture hinge on its economic viability for farmers. The current dominant cropping system of rice and mustard needs to be intensified and diversified and short-duration oilseeds should be added either sequentially or as an intercrop while taking into account the effects on the environment and soil health in an irrigated ecosystem. Additionally, the current rainfed ecosystem's rice-oilseed and rice fallow cropping system needs to be intensified through the use of resource-saving techniques such minimum or zero tillage, residue retention, mulching, etc. A comprehensive study may be conducted on the development or intensification of rice fallows, incorporating crop adjustments and advancing sowing times for optimal residual moisture utilization along with integrated crop management practices like seed priming, seed treatment etc. Additionally, an optimum agronomic package of practices for high yielding and insect, pest, and disease resistant varieties, along with the upcoming hybrids needs of rice-mustard cropping system to be worked out. Adoption of site-specific nutrient management (SSNM), precision agriculture, and conservation agriculture can bring more profits to the rice-mustard growers. Strengthen policy settings by improving understanding of them linkages with, and impacts on, food security. Achieving more productive and sustainable rice-based cropping systems will necessitate better understanding of and integration across formal and informal policies, especially in the arenas of agricultural industry and trade, land and water resources management, agricultural extension systems, and marketing systems.

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