**Effect of cultivation methods and crop establishment techniques on crop management practices, productivity and energetics in rice-wheat cropping system**

**Abstract**: The rice – wheat cropping system (RWCS) is mainly spread in Trans, Upper, Middle and even in part of Lower Indo-Gangetic plains (IGPs) and mostly grown by puddle transplanted rice followed by conventional drill-sown wheat. The various adverse effects of the presently followed cultivation methods, improvement in knowledge base especially for mechanization, residue management, land configuration and their role in resource use efficiency, awareness about ITKs and their potential to tackle the present concerns generate the call for trying new cultivation methods (CMs) and / or crop establishment methods (CEMs). The review aims discuss the variation in productivity, energetic, nutrient uptake, and changes in soil properties as well as environmental concerns across CMs / CEMs. The significant impact on water saving (aerobic rice system (ARS) and zero tillage wheat), exploring genetic potential of individual plant (system of rice and wheat intensification), ease in weed management (cono weeder and alternate wetting and drying and ARS) with several environmental concerns (herbicide resistance in weed and shift in weed flora), development of different tools/techniques for sowing (zero till seed drill, drum seed drill and happy seeder) and crop management (combine harvesters and laser land leveller) were highlighted to a great extent due to changes in CMs/CEMs. The changes in CMs/CEMs is on large extent is constrained due to lack of consistency in following new methods, low incentive to environmental friendly methods, lack of soil inherent ability to support new methods in terms of yield and non-competitiveness of new methods on socio-economical scale. On the other hand, increasing energy and cost saving, timeliness in observation, slight improvement in yield and policy initiatives are well reported reasons for adoption of new CM/CEMs in RWCS. In nutshell implementation/adoption and study of the impact of CMs/CEMs is essential considering the several alarming situation about cost: benefit analysis of farmer, subsidies on inputs required, future prospects of the RWCS, availability of options and alarming rate of natural resource degradation.

**Key words:** System of rice intensification, aerobic rice, zero tillage wheat, nutrient management.

**Introduction:**

The Indian diet have significantly affected by rice and wheat after green revolution during which promotion of modernization (new varieties, use of fertilizers and irrigation) and shifting of corps cultivation zone (rice cultivation in north western part of India and wheat to entire IGPs) were take place (Bhatt et al., 2016; Dhanda et al., 2022). The consideration of these changes is based on the urgency of increasing food supply, hypothesis that both rice and wheat will cater the food need and international support and collaborations (Pingali et al., 2001; Nawaz et al., 2019). This was holds true and significant increase in production and productivity to achieve the target of such promotion. This is seen from increasing rice and wheat production from 84.98 mt and 69.68 mt to 137.83 mt and 113.37 mt. from 2000-01 to 2023-24, respectively with significant share of both crop in food-grain production (Anonymous, 2024). At the same time share of rice and wheat in natural and artificial resource consumption also reflect it. The soil and other natural resources were in support of the crop, input and management based changes made during those time leading the conformity of rice followed by wheat as cropping system with its further spread and uniformity cross the IGPs (Prasad, 2005; Chauhan et al., 2012). The system were further adopted most of the new technology to make it consistently perform as per demand (Ladha et al., 2009; Jat er al., 2009; Ullah et al., 2021). Due to such phenomenal increase in production and urgent food need, both crops entered as major player in several long term policies with public distribution system being one (Jha et al., 2007; Bhattacharya and Ravi, 2022). This leads to responsibility (and burden over the decade) on the RWCS to contribute significantly and some time alone to meet food demand in India. The policy support was given as per requirement which leads further intensification on same land with same natural resources at increased level of inputs and managerial skills. The impact on natural resources were got least attention with consideration that input and management practices will take care and will be further modified as per the requirement of time and situation. The modification rate intensifies over the time and with increasing realization that natural resource degradation is taking place at alarming rate with several short and long term concerns in system (Timsinna and Coner, 2001; Bhatt et al., 2016; Dhanda et al., 2022). The modification in tillage system with introduction of conservation tillage based practices with zero / minimum tillage wheat (Laxmi and Mishra, 2007; Erenstein and Laxmi, 2008), modification in seed and sowing specification with introduction system of rice intensification (Thakur et al., 2010; Balamatti and Uphoff, 2017), modification in water management with practices such as aerobic rice system and alternate wetting and drying, modification in weed management with minimum tillage and availability of wide range of selective herbicides (Chhokar et al., 2007; Singh et al., 2016) were take place at different time in RWCS. The changes in CMs and CEMs are outcome of such changes with consideration of economy, ecology, policy changes and degradation of natural resource base. These changes in cultivation methods have significantly affects productivity and profitability (Shahane and Shivay, 2019; Shahane et al., 2022), resource use efficiency and soil health (Shahane and Shivay, 2021) as well as ecological impacts of RWCS which were described in present review articles. The discussion of such changes was of prime importance due to their impact will increase further as well as availability of large information about them. The potential of changes in CMs and CEMs in addressing the impact on sustainability, concerns of diversification, future socio-economic impact and capacity to utilization of modern knowledge will further intensify the need to discuss changes due to CM/CEMs.

**Rice-wheat cropping system:**

The RWCS is the single most efficient system handling the Indian food security over 5- to 6 decades and reported to have significant impact on natural resources as well as human health (Shahane and Shivay, 2024). The rice and wheat are grown on 43.9 and 30.5 million ha area in India and together contributes to 60.8 % and 75.6 % to the total area and production of food-grain, respectively; while the rice-wheat cropping system is the most important cropping system occupying nearly 10 million ha area in India. The individual contribution rice to total area and production of food-grain production is 36.6 % and 41.6 %, respectively. The expected biomass production in both crops was higher with 234.3 and 203.4 million tonnes based on the present production level of 137.8 and 113.3 million tonnes (Anonymous, 2024) and considering the ratio of residue production as given by (MNRE, 2009). The RWCS is still contributing significantly to the national buffer stock as well as procurement of food grains in India considering the major share of Punjab, Haryana and Uttar Pradesh to both crops. Being a staple food the Govt. is bound to insure the cost effective and sufficient availability of both crops leads to major share of both crop in most of Indian people diets as well as major source of nutrition to the human being (Sharma et al., 2020). The multiplicity of uses of both crops in different recipes as well as increased share in export of agricultural commodities due to crop species diversity and quality traits (*Basmati* rice and ready to cook/eat prepared products from wheat flour) further increase the footprint of both crop on food and nutritional security of the majority of population.

In term of input use the share of rice to nutrient consumption is 37 % N, 37 % P and 37 % K out of the total NPK consumed in India; while same for the wheat is 24 % N and 24 % P. The rice stands second after cotton in amount of total agrochemical used in crop production. The significantly higher water footprint of both crops were realised based on the decreasing the depth of ground water in Punjab and Haryana (Rosencranz et al., 2022) as well as amount of water used in production process of rice (2865 to 5148 litre kg-1 of rough rice) (Shahane and Shivay, 2018). Increasing new and large array of agrochemicals for weed management in both crops also signifies their footprint on the input use. The share of both crops in amount of input used is also expected to be reflected in to the subsidy given by government. This shows their impacts in economic terms at both micro and macro level. The residue burning is major concern in RWCS (Lohan et al., 2018) and the reported widely at policy front as well (NAAS, 2017). The losses of nitrogen by different way causes a significant impact on GHG emission, ground water pollution and several health concerns to living being as a whole (Kumar et al., 2021). This indicates their footprint on environmental degradation. Besides that, the increasing nutrient deficiencies, accelerating the soil degradation and reducing soil carbon content (Timsina and Connor, 2001; Bhatt et al., 2021) were further indicates their footprint on the soil resources. Considering these wide scale impact and awareness about them, there was a consistent change occurs in production processes with majority of them in crop cultivation practices. The changes in individual practices will not be having large and long lasting impact. Therefore, CM/CEMs with their changes were highlighted to a great extent in both crops and RWCS as well. These changes were describes under two major heads viz. sustainability and diversification.

The incorporation of green manuring crops in puddled transplaed rice and brown manuring in direct seeded aerobic rice (Ray and Gupta, 2001; Mandal et al., 2003), intensification through addition of summer green gram in RWCS in Trans and Upper IGPs (Sharma et al., 1995; Sharma and Prasad, 1999), incorporation/ mulching and collection of residue of rice and wheat for other uses, changes in cultivation or crop establishment techniques (Gill et al., 2006; Gangwar et al., 2008 and 2009), changes in weed management through rotational use of low dose herbicide and IWM (Ghosh et al., 2017), micronutrient fertilization (Shivay et al., 2008 and 2008a) and microbial inoculation for biofortification, site specific nutrient management (Singh et al., 2008; Khurana et al., 2008) and decision support system for nutrient management are the major options suggested for bringing sustainability in RWCS. The diversification can be achieved through replacement of rice in through maize and pulses, introduction of break crop, replacement of wheat or complete cropping system or species diversification through changing *Basmati* rice or durum wheat or barley (Shahane and Shivay 2019; Banjara et al., 2022). Along with that, diversification of nutrient sources, weed management strategy and changing water management in rice in RWCS are the other options suggested. Among these options, changes in CMs/CEMs address concern of both sustainability and diversification. The changes in CMs/CEMs lead to variation in plant and crop geometry which responsible for varying growth behaviours of crop and modification in the management practices. The CMs encompasses all management practices which including CEMs and the recommendation of inputs were also differ with change in CMs. The different CM and CEMs have varied level of positive and negative effect on natural and artificial resources which are reflected in to the yield and sustainability of RWCS.

**Potential of RWCS to be considered for study changing CM/CEMs:** The RWCS was considered for study of the impact of changes in CM/CEMs due to following points (Figure 1).

* **Diversity of production system:** The rice is grown in six different ecosystems with varied hydrological regimes (Prasad et al., 2012); while cultivation of wheat was modified to match with cultivation of previous season crop, land configuration, increased mechanization and resource saving nature of different methods. This diverse ecosystem of rice cultivation has varied soil, water and plant regimes creating different methods of rice cultivation across the country.
* **Significance in national food and nutritional security:** Both rice and wheat crop are the staple food and meet the calories and protein need of majority of Indian population. The advancement in science leading to release of bio-fortified varieties of rice and wheat again emphasises their role in food and nutritional security (Yadava et al., 2018).
* **Significance in resource consumption:** The share of rice andwheat in total food-grain production system was 41.5 % and 34.1 %, respectively; while share in total area under food-grain crops is 36.2 % and 24.1 %, respectively (Anonymous, 2024). The rice and wheat production require 3452.5 MJ and 2459.0 MJ per tonne of grain produced, respectively (Shahane et al., 2022) and if considered over total rice and wheat production, then it will be 475.75 × 109 JM and 278.60 × 109 MJ, respectively. This estimate is obviously have production system and input endowment bias due to variation in such practices but will show the rough estimate about energy consumption in rice and wheat cultivation. The rice is grown in puddle and submerged condition with 16 million ha area under irrigated wet ecosystem and 4 million ha area irrigated dry ecosystem and 1.5-2 million ha area as deep water rice (Prasad et al., 2012).
* **Faster rate of degradation of natural resources:** The sign of degradation of natural resource due to both crops are seen in RWCS followed in the trans and upper IGPs.The deterioration of soil health with decrease in organic matter content,increasing response of rice and wheat to application of micronutrients and secondary nutrients such as sulphur**,** decrease in factor productivity and stagnation in productivity (Timsina and Connor, 2001), lowering ground water level (Jalote *et al*., 2006; Hira, 2009; Jain et al., 2021) due excessive use of ground water for irrigation, increasing area under salinization created due to excessive use of canal water for irrigation (Hira *et al*., 2004; Kumar *et al*., 2010), significant deterioration of soil physical and biological properties and pollution of groundwater due to excessive use of agrochemicals including chemical fertilizers are well documented examples of resource degradation due to continuous cultivation of this cropping system by following traditional plough based system of tillage.
* **Residue generation and problems of residue burning**: The rice and wheat has largest share in total residue generation in India with total residue generation of 244.9 million tonnes from rice and 169.9 million tonne from wheat (Calculated based on the production data and harvest index (rice 0.36 and wheat: 0.40) (Anonymous, 2024). As the rice and wheat are mainly grown under intensive cropping system and large amount of residue generated, burning is preferred as management option for quick vacating the land for sowing next crop. As the residue of both rice has accountable nutrient in crop residue (Shahane et al., 2018), the burning of residue will not be a sustainable option and in such case different residue management options and CEMs such as zero tillage, minimum tillage, etc. were emerged and their suitability in production system need to be investigated.
* **Energy intensive nature of cultivation practices:** The traditionally followed puddling and transplanting of rice under unaerobic condition and drill-sown wheat requires high intense tillage and huge energy (Shahane et al., 2022). With increasing prices of petroleum oil (diesel) and increasing wages of labour along with their higher requirement for transplanting increases the energy need and ultimately the cost of cultivation. In this context study of new CEMs and CMs for their energy efficiency is needed.
* **Contribution of rice and wheat to air pollution and greenhouse gases emission**: The rice and wheat cultivation is mechanized for land preparation, sowing, inter-cultivation and harvesting and threshing through combines. This all operations are utilizing either petroleum based fuel or electricity and both cause environmental pollution through release of different greenhouse gases.

Considering the above mentioned issues of presently followed systems and availability of large array of CMs and CEMs with significant and positive impact on production and resource use efficiency, there is need to study and utilize these options. Further section of review discusses the role and significance of CMs and CEMs in affecting crop productivity, resource use efficiency and changes which will occur in packages of practices and input addition due to acceptance of any CEMs and CMs.

**Impact of CM/CEMs on crop management:**

**Nutrient management and CETs**: The area under RWCS as well as area planted individually either with rice or wheat in other cropping systems responds to the nutrient application because of the following reason:

1. Use of high yield varieties with higher seed replacement ratio in both crops leading to high nutrient uptake.
2. Decreasing addition of organic manure due to increasing prices of organic sources of nutrition as compared with chemical fertilizers and increased mechanization (less or no more draft animal for tillage and other operation).
3. Imbalance use of nutrient tilted mainly towards the primary nutrients and less attention to secondary and micronutrients.
4. Significant response to application of micronutrients and promotion of same as a strategy for bio-fortification of crops.
5. Both crops were grown in intensive cropping system under irrigated condition leading to higher nutrient uptake and ultimately response to fertilization.
6. Decreasing factor productivity and increasing intensity of short and long term problems in RWCS (Bhatt et al., 2021) which also reduce the intensity of response of crop.

The variation in nutrient management among CEMs was arises due to the variation in the hydrological regimes, seedbed preparation (puddling), amount of crop residue retention and more recently due to following resource conservation technology such as green manuring (Islam et al., 2014) and brown manuring practice (Reddy et al., 2022) and tillage system. The submergence which is common in puddle transplanted rice. It is reported to have significant impact on increasing phosphorus availability and enhance the iron (Fe) and manganese (Mn) availability, moderation effect on soil pH (Sidhu et al., 2006; Asenso et al., 2022) and losses of nitrogen through greenhouse gases (Ahmed et al., 2023). They reported that availability of Fe and Mn is increased due to reduced condition of soil and due to decrease in soil redox potential of soil. The pH of soil also has significant role to play in this regards to nutrient availability in soil. On the other hand, submergence also reported to increase soil pH thereby reduce concentration and ultimately toxicity of Fe and Mn which is well known in acidic soil. The submergence is also reported to make rice crops as option for growing under problematic soil such as acid sulphate soil, saline soil and alkaline soil (Huang et al., 2022). The submergence and soil puddling also affects the soil physical properties such as soil strength, porosity and bulk density (Singha et al., 2022) which will also affect the nutrient mobility (diffusion) and their availability to rice. In case of zinc (Zn), the availability is increased by temporal submergence; while the soil continuously under reduced condition leads to decrease in Zn availability. The submergence play important role in inter-convergence of NO3- and NH4+. The top few centimetre layer is act as oxidized zone and remaining soil is under reduced condition. Application of NO3- in recommended to apply in oxidized zone while NH4+ in reduced zone in order to avoid the losses due to denitrification and volatilization, respectively (Prasad et al., 2012).

In SRI methods use of organic sources of nutrition and microbial inoculations is also considered which positively affect the soil microbial population (Midya et al., 2021; Shahane and Shivay, 2024). The increase in soil enzymes activity (dehydrogenase, alkaline phosphatase and microbial biomass carbon) in SRI, PTR and ARS was reported by Shahane and Shivay (2024) and CDW, ZTW and SWI in Shahane et al. (2023). They reported that, both PTR and SRI soil conditions are suitable for the growth of Algae which has significant contribution to the biological nitrogen fixation. This was reflected in significantly higher growth and yield in rice. In direct seeded upland rice or aerobic rice system, iron deficiency is common (Tamuk et al., 2024) and submerge of soil for few days was suggested to alleviate this deficiency. The root growth and diffusion of nutrient especially P will be affected significantly under upland or ARS.

In recent years, retention or incorporation of crop residue of previous season crop was followed on large area in RWCS in Trans and Upper IGPs. In rice and wheat 89-90 % and 86-88 % of absorbed K is remained in straw; while same for N and P is 46-47 and 37-39 %, respectively in rice and 25-26 % and 22-23 % in wheat (Shahane et al., 2018). The nutrients are available after decomposition of residue which being slow due to wider C: N ratio of rice and wheat. At the same time, this addition of crop residue also causes immobilization of nutrient specially nitrogen in early stage of decomposition which causes the nitrogen deficiency. The resource conservation technology such as brown manuring mainly followed in upland rice of in ARS contributes significant quantity of nitrogen and other nutrients (Reddy et al., 2022). The green manuring of *Sesbania aculeate* with 75 % RDN in rice increases total nitrogen uptake by 25.4 kg/ha over application of 100 % RDN and increase grain yield 637 kg/ha (Islam et al., 2014). The improvement in organic matter of soil also significantly contributes to the crop nutrition. Considering this variation in behaviour of nutrients across CEMs, the amount, timing and method of nutrient applications are differ across CEMs.

In case of wheat, the nutrient application is depending on the residual effect of last season rice, tillage practices, amount of residue retention or incorporation and crop/ variety response. In conventional drill sown wheat, most of the crop residue was removed and field is till with 2-3 pass of cultivator and/or rotavator. The residual effect is restricted only up to nutrient remained in the soil after harvest of crops grown in *kharif* season. Amanullah and Inamullah (2016) reported that increase in P application rate and zinc from 0 to 120 kg P/ha and 0 to 15 kg Zn/ha respectively in rice, increases its residual effect of in wheat grain yield indicating residual effect of both nutrients on wheat yield. In case of sources, use of organic sources was emphasised in system of wheat intensification (SWI) and SRI system in early years of adoption (Dobermann, 2004; Barison and Uphoff, 2011); while in other CEMs there is no any such specifications. The amount of nutrient applied is differs with respect to residue retention/ incorporation across CEMs (Sharma and Dhaliwal, 2020). Increase in soil organic carbon level due to continuous addition of residue may be the reason for the same (Sharma et al, 2016). The nutrient use efficiency (nitrogen/ phosphorus/ potassium) in FIRB was reported to be different (Kumar et al., 2022) which create scope making changes nutrient recommendation. The system based approach will different for each combination of CMs/CEMs in RWCS leading to scope for further evaluation of nutrient requirement and efficiencies across the different combination.

**Weed management:** The rigor of weed management in one crop will affect the weeds population and dynamic in succeeding crops over and above the crop and region specific weed flora of a particular crop. The changes in tillage (type, frequency and timing) across the crop establishment methods are well accepted across CMs/CEMs due to which weed dynamics will be significantly affected (Table 1). The conservation agriculture based tillage practices were widely reported for changes in the weed dynamics of annuals and perennial weeds. These types of tillage system involve intensive use of herbicide leading to distinct impact on the weed population. The impact of puddling on weed is classically cited since long due to its potential against the weed management; while the changes in weed across the PTR and ARS was expected due variation in hydrological regime. The changes in weed across the different rice based ecosystems were also reported by different workers (**Table 2**). The use of cono weeder in SRI need arable condition and therefore it will also have impact on weed flora change in SRI over PTR. The impact of use of weedicide was highlight to a great extent through shifting weed flora in wheat and increase in resistance of weed to different herbicides (Soni et al., 2023; Rao et al., 2020).The direct seeded aerobic rice is well cited example of huge losses due to weed population and difficulty to management through mechanical approach; Hence use of herbicides is expected with increase in range of herbicide available for direct seeded aerobic rice. The residue retention will be another variable affecting the weed dynamics due to creating hindrance for germination and growth of weeds. The stale seed bed technique generally followed with conventional drill sowing helps in exploiting the weed seed bank and also further enrichment of it due to reducing changes of seed setting of weeds.

Table 1. Effect of CM/CMEs on weed management in different rice ecosystems and wheat cultivation methods

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| **S. No.** | **Tillage system weed management practices** | **Major findings** | **References** |
| 1. | Conventional tillage in RWCS (direct seeding of rice) is compared with zero tillage in RWCS for rice and wheat | The weed biomass recorded at frequent interval found consistently higher in ZT than conventional tillage in both crops for all three years of study. The yield of rice and wheat was also higher in both rice and wheat conventional tillage over zero tillage. | Alhammad et al., 2023 |
| 2. | Transplanted rice, direct seeded rice and SRI were compared for rice yield and weed nutrient uptake | The direct seeded rice found inferior to both SRI and transplanted rice in dry biomass accumulation of rice and grin yield of rice in both year of study. The share of weed in total nutrient uptake was found highest (10.68 and 2.66 %) in direct seeded rice as compared to transplanted rice (3.14 and 0.69 %). | Nazir et al., 2022 |
| 3. | Comparison of cultivation methods in rice for weed parameters and rice yield. | Weed density and weed dry matter accumulation at 30 days and 60 days after sowing in dry direct seeded rice was higher than transplanted rice. Similarly rice grain yield in transplanted rice (6.94 t/ha) was higher than that of direct seeded rice (6.04 t/ha) | Jehangir et al., 2021 |
| 4. | Comparison of aerobic rice SRI and conventional flooded transplanted rice (CFTR) for grain yield and water productivity for two years. | The water productivity of rice in SRI (0.76 kg grain m-3 of water) is higher by 0.2 kg grain m-3 of water over CFTR. The grain yield in SRI (6.21 t/ha) was higher by 290 kg/ha over CFTR (5.92 t/ha). | Midya et al., 2021 |
| 5. | Two year study involving four crop establishment methods in wheat viz., zero tillage with residue, zero tillage without residue, zero tillage without residue burning and conventional tillage. | The lowest weed dry matter was recorded in zero tillage with residue (12 g m-2) which is significant lower than conventional tillage (18 g m-2). The yield in zero tillage with residue recorded significantly higher yield (3.86 t ha-1) which is higher by 630 kg ha-1 over conventional tillage (3.23 t ha-1). | Kumar et al., 2018 |
| 6. | Comparison of dry seeding, wet seeding and drum seeding methods for weed population and dry matter accumulation in rice | The drum seeding had significantly lower weed density and weed dry matter accumulation for grasses, sedges and broad-leaf weeds at 40 DAS and 60 DAS compared to wet and dry seeding. Besides that grain yield in drum seeding (4.55 t/ha) was significantly higher than wet seeding (4.27 t ha-1) and dry seeing methods (3.97 t ha-1). | Singh and Singh, 2010 |
| 7. | Comparison of four methods of crop establishment of rice viz., dry seeding, drum seeding, zero tillage and transplanting were compared for their effect on yield and weed dry matter accumulation. | Transplanting methods found best with lowest weed dry matter accumulation at harvest (35.0 and 15.3 g m-2) in first and second year, respectively) and higher grain yield (5.472 and 5.529 t ha-1) as compared to methods of crop establishment. | Yadav and Singh, 2006 |
| 8. | Three methods of direct seeded rice viz. wet seeding, dry seeding and zero tillage seeding were compared. | Total weed density and dry matter accumulation at 30 DAS and 90 DAS was found lowest in zero tillage; while it remain on par with other methods. The rice grain yield was highest in wet seeding (1992 kg ha-1) as compared to zero tillage (1819 kg ha-1) and dry seeding (1745 kg ha-1). | Rajendra Prasath et al., 2020 |
| 9. | SRI, manual transplanting and mechanical transplanting were compared for weed population and rice yield in rainy and winter season rice for two years. | Total weed population (g m-2) at 20, 40 and 60 DAT in both rainy and winter season rice was significantly lower in SRI; while grain yield was significantly higher in SRI (6.1 and 6.5 t ha-1) in both years over manual and mechanical transplanting. | Duttarganvi et al., 2016 |

**Water management:** The significant different in irrigation practices exist across the CMs/CEMs in rice which make it to be differentiated in different production system. The practices such as puddling, alternate wetting and drying, aerobic /upland soil condition, zero tillage wheat, changes in crop varieties, changes in water pricing policies and electricity for agriculture and varying surface and ground water utilization patterns affect the water management consideration in RWCS. The significant increase in water use efficiencies in SRI without yield penalty and ARS mostly with yield penalty is one most important reason for their promotion (Shahane et al., 2018; 2022); while alternate wetting and drying also reported with save water with significant different over the area. Based on the meta analysis of 323 on-farm study and 9 on-station studies Chakraborty et al. (2017) find that, direct seeded rice under wet tillage and direct seeded rice under zero tillage are best alternative in rice with water saving and economics superiority over transplanted pudddled rice. In a study conducted by Yadav et al. (2014) different wet tillage/ puddled (transplanted and surface seeded) and dry tillage (non-puddled transplanted, non-puddled surface seeded and non-puddled drill sown) methods were evaluated for their yield and water productivity in wet season and dry season. The rice yield in dry season (5.81 t/ha) was significantly higher than wet season (3.92 t/ha); while the input water productivity was remain on par in both season (0.24 versus 0.18 g kg-1). The direct seeded rice and non-puddled transplanted rice in dry season recorded highest input water productivity (0.28 g kg-1); while puddled transplanted rice in dry season (6.28 t ha-1) recorded highest grain yield. This indicates excessive rainwater and yield reduction due to other biotic tresses in wet season as well as control over water supply during sty season affect both yield and water productivity. Besides that partial factor productivity, internal use efficiency and nitrogen harvest index were also higher in dry season (Table 2). Such variation in water productivity and water saving across CMs/ CEMs helps in taking well informed decision about selection of CMs/ CEMs in RWCS as well as determine their impact yielding ability of RWCS.

Table 2. The effect of CMs /CEMs and irrigation practices in RWCS

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| S. No. | CMs/CEMs | Irrigation practice | Major findings | References |
| 1. | Puddled transplanted rice (PTR), system of rice intensification (SRI) and Aerobic rice system (ARS) in rice; while drill sown wheat (DW), wheat intensification system (WIS) and Zero tillage wheat (ZTDW) for wheat | Continuous flooding in PTR, flooding after flowering stage in SRI and field capacity moisture content in ARS. | The saving of irrigation water by 21.9 % and 27.4 %, in first and second year, respectively in SRI over PTR was reported. In case of ARS saving in irrigation water of PTR was 37.4 % and 50.8 %, respectively in first and second year, respectively.  In case of wheat significantly higher water productivity was reported in ZTDW as compared to other methods which are mainly due to higher yield in ZTDW. | Shahane et al., 2018; Shahane et al., 2022. |
| 2. | SRI, Integrated crop management (ICM) and conventional rice culture (CRC) were compared for water productivyt | For SRI and ICM, soil is kept at saturation during vegetative growth stage and a thin layer 1-3 cm is maintained during reproductive growth stage; while in CRC, 5-6 cm of water is maintained from transplanting to grain filling stage. | The water productivity in ICM is 14.66 kg/ha/mm which is significantly higher than CRC (11.52 kg/ha/mm). The yield in ICM is increased by 805 kg/ha. | Singh and Chakraborti, 2018. |
| 3. | Six crop establishment methods viz., dry direct sowing, drum seeding, SRI, Machine planting and transplanting were compared for yield and water productivity. | - | The highest grain yield was recorded in machine planting (5210 kg/ha) which is higher by 440 kg/ha than transplanting (4770 kg/ha). The water productivity was highest with SRI (5.09 kg/ha-mm) which is higher by 1.20 kg/ha-mm over transplanting method (3.89 kg-hamm). | Upendra Rao et al., 2020 |
| 4. | Four methods of rice establishment for four year viz., puddled transplanted rice (continuous flooding- PTR-CF), puddled transplanted rice (intermittent flooding – PTR-IF), direct seeded rice on flat bed (DSR-F) and direct seeded rice on raised bed) (DSR-B were compared. | In PTR-CF water level is maintained to 5 cm depth and irrigation were given when water level reach to 2 cm depth; for PTR-IF irrigations were given when soil moisture potential reach to 10 kPa at 15 cm depth, In DSR-F and DSR-R, irrigation were given when soil when soil moisture potential reach to 10 kPa at 15 cm depth. | The highest irrigation water productivity was reported in DSR-F (8.8 kg ha-1 mm-1) which is significantly higher than both PTR-CF and PTR-IF. At the same time, the rice grin yield was highest in DSR-F and found statistically superior over PTR-CF. | Mandal et al., 2009. |
| 5. | Four methods of rice establishment (direct drilling in dry field, direct seeding of sprouted seed, manual transplanting and mechanical transplanting) and four methods of wheat establishment (Conventional till sowing, zero till sowing, strip till sowing and bed planting) were compared for RWCS productivity and water productivity. | - | Rice equivalent yield of system was highest in direct seeding of sprouted seed in rice (11.46 t ha-1) and zero till sowing (11.88 t ha-1) in wheat. The highest water productivity was recorded in direct drilling in dry field (65.78 kg ha-1 cm-1) in rice and strip drill sowing (67.87 kg ha-1 cm-1) in wheat. | Jha et al., 2011 |
| 6. | The crop establishment methods of rice such as puddled and unpuddled transplanted rice, zero till transplanted rice and zero till direct seeded rice and conventional till wheat and zero till wheat were compared for their yield and water productivity. | - | The highest system productivity was observed in zero till direct seeded rice followed by zero till wheat in both years (11.01 and 11.11 t/ha) which is higher by 1950 and 2230 kg/ha over puddled transplanted rice followed by conventional till sown wheat. The system irrigation water productivity was also found highest in same treatment (68.4 kg/ha-cm) with increase of 21.6 kg/ha-cm over puddled transplanted rice followed by conventional till sown wheat. | Nandan et al., 2018 |

**Residue management:** The crop residue management is one of the important reasons for variation of CMs/CEMs in RWCS with edge to those technologies which have capacity of handle large volume of crop residue in short time. The development of harvesting techniques/ implements of rice (Ramulu et al., 2023) and sowing tools /implements for wheat leads to adoption of conservation agriculture based practices in RWCS is major factor cause changes (Sidhu et al., 2015). The short time for residue management, lack of suitability of use of crop residue as animal feed, multiple uses of crop residue (energy generation) and drastic reduction in use of animals for field works makes changes crop residue utilization. The potential of zero tillage and minimum tillage in effectiveness in handling the residue with partial retention/incorporation were reported with slight changes in fertilization and seed and sowing specifications (Gangwar et al., 2006; Singh et al., 2022). As there are mixed effect (both positive and negative) of residue utilization in-situ, their adoption is subjective to region, level/access to mecahnization and use pattern of residue. The expected promotion of organic manure generation from crop residue will add again one important option for residue utilization. In most cases the positive effect of residue utilization was reported to occur in long run and significance of residue burning in in short run in terms of ease in cultivation of rice and wheat and increases in productivity slight in due to potassium availability is also deciding factors for in-situ utilization patterns of crop residue utilization. Kaur et al. (2021) observed that, physical properties such as infiltration rate (20.6%) and percolation (18.7 %), chemical properties such as organic carbon (43.9 - 66.7 %) and organic matter (18 %) and biological properties such as microbial biomass (90-95 %) and microbial population was increased due to residue incorporation. This signifies the complex interaction of residue management options and CMs/ CEMs which need to be given weightage in order to reach at best options for higher yield, reduce burning, enhance soil health and economise RWCS.

**Impact of CEMs/ CM on energetics of RWCS:** The energy efficiency of modern conservation agriculture based technologies is one of the important reason for changing the CMs and CEMs in India from conventional plough based tillage to conservation tillage in India (Sharma, 2021). The energy consumption in fertilizers, irrigation and in tillage are the major contributor of energy input in RWCS (Shahane et al., 2022) and these components of crop production in affected by changing the CMs / CMs directly or indirectly. The use of low water requiring DSR, use of microbial inoculation, incorporation of green or brown munching, use of leaf colour changes will contributes indirectly by increasing yield and reducing energy inputs; while tillage is most highlighted in regards to reducing the use of energy in crop production. Alam et al. (2020) reviewed impact of rice establishment techniques and found that, direct seeded rice can be preferred over conventional puddled transplanted rice for reducing global warming potential; while reduces net GHG emission; while increase N2O emission. They also reported that adoption decision of CEMs differ with agro-climatic condition, demography and farm topologies and no any single method will address all concerns in conventional puddled transplanted rice. The role of zero tillage in reducing energy requirement in wheat cultivation IGPs was well reported (Kakraliya et al., 2022) with its multiple significance viz., timeliness in sowing, cost effectiveness and improvement in technical advancement. Considering various amount of energy required for different CMs/ CEMs, it will be worthy compare them for energetics (Table 3). The superiority of conservation based tillage, effectiveness in direct seeded and more energy required in conventional CMs/ CEMs are observed across the literature indicating their potential for RWCS.

Table 3. The energetic of rice and wheat affected by cultivation methods and crop establishment methods.

|  |  |  |  |
| --- | --- | --- | --- |
| **S. No.** | **CEMS/ CMs** | **Major findings** | **References** |
| 1. | Four crops establishment of rice (Direct dry seeding by zero till drill, Direct dry seeding by drum seeder, hand transplanting and mechanical transplanting) and four crop establishment methods of wheat (Rotavator till drilling, conventional sowing, strip till drilling and zero till drilling) were investigated for their energetics. | Mechanical transplanting results in highest energy output (1,03,866 MJ/Ha) and energy efficiency (5.62) in rice; while in wheat, conventional sowing resulted in highest energy output (1,39,976) and zero till drill showed highest energy efficiency (6.46). | Bohra and Kumar, 2015 |
| 2. | Three methods of rice establishment (Direct seeded rice, non-puddled transplanted rice and puddled transplanted rice) were compared in rice-cowpea cropping system for energetic and productivity. | The lowest energy input was recorded in DSR (25.50 × 103 MJ ha-1) in both years; while highest energy use efficiency (8.63 and 8.54) was recorded in same methods over both puddled and non-puddled transplanted rice. The grain yield of rice is remains on par in all three methods of rice establishment. | Giri et al., 2020 |
| 3. | Four methods of rice establishment (direct drilling in dry field, direct seeding of sprouted seed, manual transplanting and mechanical transplanting) and four methods of wheat establishment (Conventional till sowing, zero till sowing, strip till sowing and bed planting) were compared for RWCS energetics. | The lowest energy input and highest energy use efficiency was recorded in direct drilling in dry field for rice and zero till sowing in wheat. | Jha et al., 2011 |
| 4. | Puddled transplanted rice (PTR) and non-puddled transplanted rice (NPTR) was compared for productivity and energetics for two years. | The PTR recorded significantly higher grain (3.75 t ha-1) yield of rice which was increased by 530 kg/ha over NPTR. In case of energetics, net energy returns (46.8 versus 38.4 × 103 MJ ha-1), energy ratio (1.90 versus 1.50), energy productivity (0.062 versus 0.049 MJ ha-1) and energy profitability (0.90 versus 0.50 MJ ha-1) was higher in NPTR; while energy output and energy output efficiency was found higher in PTR. | Kumar et al., 2017 |
| 5. | Three system in RWCS were followed which includes, puddled transplanted rice – conventional drill sown wheat, system of rice intensification – system of wheat intensification and aerobic rice system – zero tillage wheat. | The new energy production was highest in aerobic rice system – zero tillage wheat (273.5 × 103 MJ/ha and 272.7 × 103 MJ/ha) in both years of study which was found significantly higher than other combinations of CEMs. | Shahane et al., 2022 |

**Conservation versus conventional practices**

**Mechanized versus manual**

**Transplanting versus direct seeding**

**Puddled versus non-puddled (aerobic)**

**Figure 1. Over view of cultivation methods (CMs) and crop establishment methods (CEMs) in rice-wheat cropping system (RWCS)**

**Conclusion:** The changes in CM/CEMs is taking place on a great expent with cost and energy effectiveness as major gain; while changes in labourers availability, wage rate, increased mechanization with large array of mechanical tools and implements being available, increase the range of herbicide available and stagnating productivity due to commonly followed cultivation methods are the other major reason for changing CM/CEM in RWCS. The diversity of crop promoted by policy (for rice in Trans and Upper IGPs), institutional efforts and increasing awareness about potential of organic nutrition such as green manure brown manures as well as summer legume cultivation further promote the changes in CM/CEMs. The awareness about degraded natural resource base, availability and popularity of conservation agriculture based practices, policies for organic farming and / or natural farming will expected to further intensify the changes CM/CEMs.

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