Plant Genetic Resources: Characterization and Utilization

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Research Article

Cite this article: Kapoor C *et al*. (2023). Rice genetic resources for organic agriculture under hill ecology: evaluation and usefulness. *Plant Genetic Resources: Characterization and Utilization* **21**, 159–165. https://doi.org/10.1017/S1479262123000576

Received: 20 May 2022
Revised: 26 July 2023
Accepted: 26 July 2023
First published online: 23 August 2023

Keywords:
Conventional variety; hill agriculture; landraces; organic rice; organic variety

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Rice genetic resources for organic agriculture under hill ecology: evaluation and usefulness

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Abstract

Rice cultivation in hills is challenged by sub-optimum weather conditions, low soil fertility, low temperature and moisture stress which impedes in attaining high productivity. To address this, four studies were carried out at ICAR Sikkim Centre, Gangtok, India to evaluate relative performance of local organic cultivars and conventionally bred varieties under an organic farming system. Conventionally bred varieties yielded significantly higher (45%) than local cultivars under recommended timely sown conditions whereas local cultivars showed superiority in grain yield under late sown conditions coinciding with low temperature during flowering to grain filling. Genotypes did not show significant interaction when organic or conventional production conditions were compared. For grain yield, there was a significant variation for variety × year interaction under organic system. Local organic cultivars had reduced grain yield and associated traits under rainfed upland conditions. Panicles per unit area had a significant positive association with grain yield in all production environments (organic lowland, organic upland, conventional lowland and conventional upland). Overall, the study indicates using local cultivars as donors for specific stress tolerance traits in background of high yielding genotypes to enhance rice yields sustainably under organic system in hills.

Introduction

Rice is one of the major staple food crops in hill states of India. Rice germplasm endemic to the Himalayan region has traits conferring resilience to various biotic and abiotic stresses that challenge rice production in hills (Rana *et al*., 2009; Imam *et al*., 2013; Mehta *et al*., 2014; Umakanth *et al*., 2017; Husaini and Sofi, 2018; Najeeb *et al*., 2021). Among hill ecologies, the North Eastern (NE) region of India holds special status owing to its rich diversity in rice genetic resources including unique rice landraces (Hore, 2005; Choudhury *et al*., 2013; Choudhury *et al*., 2014; Ngachan *et al*., 2014; Roy *et al*., 2015). In the last decade organic agriculture has increased globally as agriculture develops towards chemical free and ecologically safe methods of food production and biodiversity compared to conventional farming (Gabriel *et al*., 2010; Tuck *et al*., 2014).

Hill states in India have been leading the adoption of organic farming. Sikkim, a constituent state of NE region of India, is one of the biodiversity hotspot regions in Eastern Himalayas, and has achieved 100% organic status supported by its agrobiodiversity richness and ecologically sustainable farming systems. Rice production under organic conditions in hills is challenged by low soil fertility, early onset of low temperature and low sunshine hours constituting a complex low production environment. Soils of Sikkim are poor in water holding capacity hence rice cultivation under upland conditions faces low moisture stress at critical stages of growth which finally affects grain yield. Low temperature during flowering and grain filling stage affects rice yields due to spikelet sterility and poor grain filling resulting in chaffy grains.

Breeding specifically for organic and low input conditions is essential for improved productivity (Murphy *et al*., 2007; van Bueren *et al*., 2007; van Bueren *et al*., 2011; Crespo-Herrera and Ortiz, 2015; Huang *et al*., 2016; Nuijten *et al*., 2017). While several studies have proposed that organic farming can provide sufficient yields for food production (Liu *et al*., 2016; Muneret *et al*., 2018; Eyhorn *et al*., 2019; Krauss *et al*., 2020), others have been sceptical of this premise due to reported lower yields (Kirchmann *et al*., 2008; de Ponti *et al*., 2012; Seufert *et al*., 2012; Gabriel *et al*., 2013; Ponisio *et al*., 2015). Studies to assess the performance of rice varieties under organic systems have been undertaken (Dubey, 2016; Manjunatha *et al*., 2016; Singh *et al*., 2017; Vanaja *et al*., 2017;

Mandi et al., 2018; Kumari and Shanmugam, 2020). However, rice improvement for organic systems is in nascent stage. Currently in India, high yielding rice varieties cultivated in organic farming originate from breeding programmes from conventional agriculture. A breeding programme specifically for organic systems requires separate resources and testing specifically under organic farming conditions

Local rice cultivars dominate rice farming under organic agriculture along with a small share of high yielding varieties (HYVs). Rice HYVs have already proved their potential in conventional systems however their suitability and usefulness under organic conditions in hilly ecologies needs further evaluation for current and future rice improvement programmes. To address this, we carried out studies on local and conventional rice genetic resources to evaluate (i) traits and their associations affecting rice yield under organic conditions and interaction of rice genotypes with system of cultivation and (ii) suitability of genotypes and traits affecting rice yields under low temperature stress in hill ecology.

Materials and methods

Experimental site

Trials for the study were conducted at research farm of ICAR Research Complex for NEH Region, Sikkim Centre located at Tadong, Gangtok, India at 27°32′ N latitude and 88°60′E at an altitude of 1320 m amsl (Fig. 1). The site represents mid hill temperate type climate. The field experimental site is a certified organic farm and has been under organic management since 2003. The soil of the site is sandy loam in texture and moderately deep with pH of 5.97 and soil organic carbon content of 1.38. Nitrogen content of the site plots is medium i.e. 340 kg N/ha. The site has both irrigated rice fields for lowland rice trials and upland fields for direct sown rice. Weather parameters during the testing years have been shown in online Supplementary Table S1. The experimental site can be categorized as low to medium yielding location among tests sites under hill ecology with mean experimental grain yield of 3249 kg/ha recorded in different All India Coordinated Rice Improvement Programme (AICRIP) trials for medium duration irrigated conditions of hills.

Experimental material

A total of 420 rice genotypes (online Supplementary Table S2) were included in the study which comprise of local organic rice cultivars of Sikkim, improved varieties of ICAR-VPKAS, Almora, Uttarakhand, Rice & Wheat Research Centre, CSK HPAU, Malan, Himachal Pradesh and ICAR Research Complex for NEH Region Tripura Centre, Lembucherra, Tripura. Local varieties of Sikkim are annotated as 'organic varieties' as these have been in cultivation under organic farming and have been adapted to local agro-ecology whereas the lines procured from outside are referred as 'conventional' varieties bred for higher grain yield under conventional management using inorganic fertilizers/chemicals.

Trials and layout

A total of 420 rice entries were included under four different research trials (online Supplementary Table S2) to study response of local organic cultivars and conventional varieties under organic system. Data for upland rice trials were taken from experiments conducted during *kharif*, 2013 and 2014 while for irrigated conditions trials were conducted during *kharif*, 2018 and 2019. The trials were raised under organic management in which farm yard manure @10 tonnes/ha was applied in the plots before 15 days of transplanting. Organic manure containing Bio-NPK were applied at 30 days post transplanting. Thirty day old seedlings were transplanted for irrigated trials keeping two seedlings per hill while seed was sown directly in lines for upland conditions at plant spacing of 20 × 15 cm. Fields were kept weed free by hand weeding at different crop stages. Trials conducted for different studies were as follows:

Relative performance of local organic cultivars under irrigated and rainfed upland conditions

Fifty local organic rice cultivars commonly cultivated in Sikkim (online Supplementary Table S3) were evaluated for relative performance under irrigated transplanted and direct sown rainfed upland conditions. The entries were tested in augmented block design with four checks following organic practices during *kharif* 2013 & 2014. Entries were adjusted in five blocks with 14 entries each. A single row of each entry was sown in 3 m row length maintaining plant spacing of 20 × 15 cm. Plant to plant spacing under upland conditions was maintained by thinning the seedlings after two weeks of sowing in each line.

Data were recorded on plant height (cm), days to 50% flowering, number of tillers per plant, panicle length (cm), days to maturity, grain yield per plot (g) and test weight (g).

Yield performance and trait association under low temperature stress

Two hundred and twenty one rice entries comprised of popular local landraces, released varieties and advance breeding lines were tested for low temperature tolerance during *kharif* 2018 and 2019 under organic conditions. For coinciding with low temperature during flowering and grain filling stage, transplanting was delayed by one month (first week of August) of normal transplanting (first week of July). The entries were tested in a randomized block design with two replications with spacing of 20 × 15 cm. Performance of the entries were assessed for plant height (cm), panicles per m^2, yield per panicle (g), yield per hill (g) and yield per m^2 (g).

Relative yield performance and trait association under timely and late sown conditions

A total of sixty three entries comprised of local organic cultivars and released HYVs were tested for their relative performance under timely and late sown conditions under organic management. The entries were tested in randomized block design with two replications keeping spacing of 20 × 15 cm. Thirty day old seedlings were transplanted at normal recommended time (first week of July) and also under late conditions (first week of August). Nursery for delayed transplanting was sown one month after the normal nursery sowing time. Data were recorded for plant height (cm), yield per plant (g), yield per hill (g) and yield per m^2 (g).

System × variety interaction of traits affecting grain yield

Eighty six rice cultivars were tested at three locations under AICRIP for hills at Gangtok (Sikkim), Almora (Uttarakhand) and Rajouri (J&K) during the year 2018 and 2019. Trials at Gangtok location were conducted under organic conditions while trials at Almora and Rajouri were undertaken following conventional practices. The entries were tested in randomized block design in three

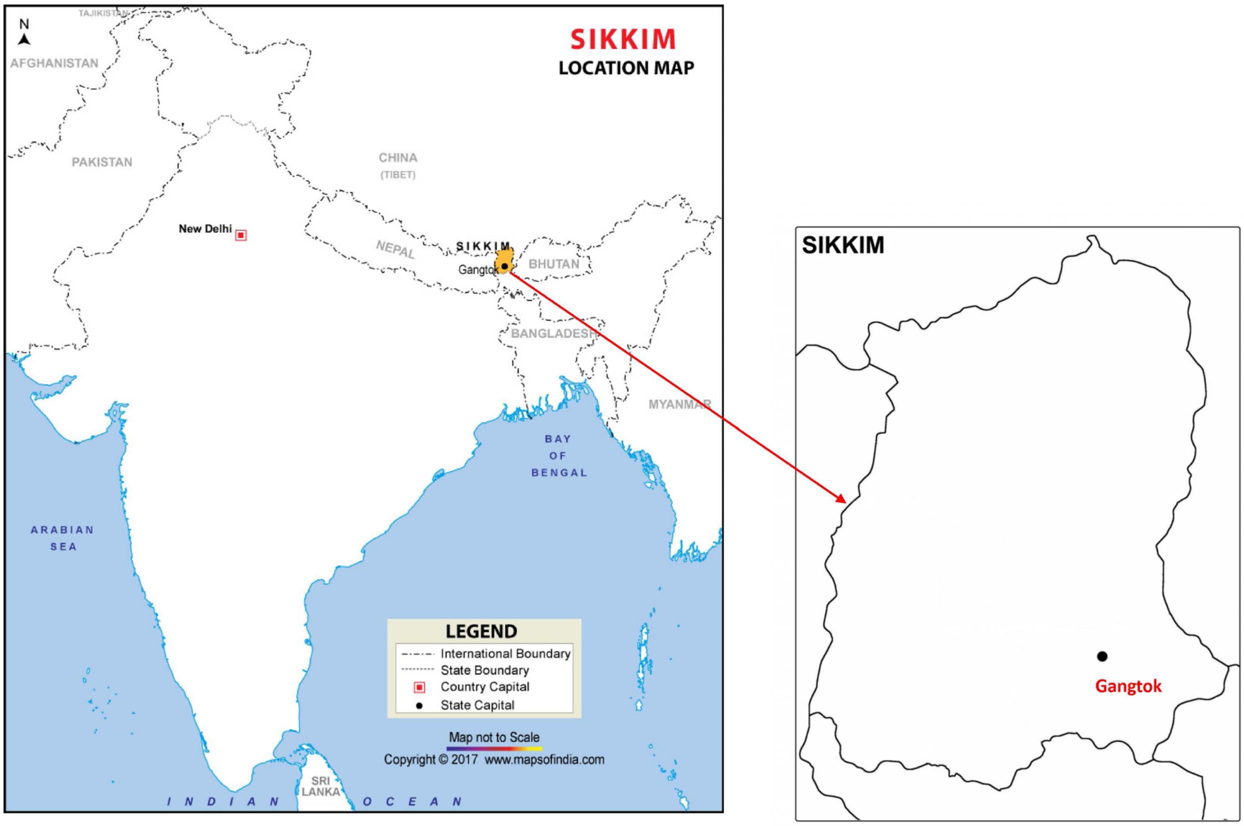

Figure 1. Location of the experimental site at Gangtok, Sikkim.

replications. Data were recorded for plant height (cm), days to flowering, panicles per m^2 (g) and grain yield per ha (kg).

Statistical analysis

ANOVA for randomized block design was calculated using proc glm function of SAS 9.3. Analysis of variance for augmented block design was calculated as per Federer (1956). Associations among the recorded traits were computed using Pearson's product moment correlation using statistical software SAS 9.3. Before carrying out correlation coefficient test for linearity of the data was ascertained by performing regression test using scatter plot.

Results

Mean maximum and minimum temperature under timely sown conditions was 27.17 and 19.34 °C, respectively during flowering while the same averages to 26.08 and 15.09 °C during grain filling and maturity. In comparison, mean maximum and minimum temperature under late sown conditions was 25.15 and 15.86 °C, respectively during flowering while it further lowers to 22.65 and 11.61 °C during grain filling and maturity stage creating a sub-optimal temperature for rice growth (online Supplementary Figs S1a and S1b).

Relative performance of local organic cultivars under irrigated and rainfed upland conditions

Local organic rice cultivars exhibited variable response under irrigated and upland environment. ANOVA for augmented block design for both conditions is shown in online Supplementary Tables S4a, S4b.

The per cent increase or decrease in trait values of seven metric traits under both the production environments is shown in online Supplementary Table S5. Except for cultivars Taichung, Takmaru, Zokub, Takmaru (L), Kalo Dhan and Red Zomu, all other rice cultivars showed reduction in plant height ranging from (−) 73.58% reduction in Tulasi to (−)1.35% in Bael Buty. Red Zomu recorded 16.9% increase in plant height under upland conditions. Early flowering was observed in Sano Khamti, Takmaru (L), Zornalli, Chirakey, Tabrey, Ramsaree, Doodhkalam, Pahelo Dalle and Kalo nunia. Days to flower remained unchanged for cultivars Nepal Dhan, Timburey, Kalo Dhan, Anandhi, Marsee, Kataka, Kalsati, Zomu and Bael Buty. Tillers per plant were significantly reduced under upland conditions where forty three cultivars showed reduction in tillers per plant with maximum reduction in cultivar Sijali (−) 151.85% to minimum in Phool patta (−) 1.69%. Conversely, cultivars Tabrey, Takmaru (L), Kataka, Sano Khamti, Kalsati, Sano attey and Chirakey recorded relatively higher number of tillers/plant under upland conditions with maximum gain in cultivar Chirakey (+) 32.73%. Except for Rambhog, Attey, Thulo Attey, Zornalli, Marsee and Takmaru all other cultivars showed reduction in test weight ranged from (−) 24.96% to (−) 0.16%. Out of 50 cultivars, 36 showed more than 10% reduction in grain yield per plant under upland conditions. However yield in cultivars Takmaru (L), Khimti, Sano Khamti, Champey, Kalo nunia and Krishna bhog remained unaffected and showed gain in grain yield by 10% as compared to their relative yield under irrigated environment. On other

https://doi.org/10.1017/S1479262123000576 Published online by Cambridge University Press

hand drastic yield reduction was noted in Jhapaka, Bhangeri, Japani, Attey, Phouryal and Musuli. Cultivars recorded numerically higher grain yield per plant under irrigated conditions than the best check (PD-10) were Japani, Taichung, Kaley Bungey, Dudhey Juari and Pahelo Dalle whereas under upland environment Takmaru (L), Champey, Sano Khamti, Takmaru, Taichung, Pahelo Dalle, Zokub, Nepal Dhan, Khimti yielded higher than the best check (Bhalum-3). Mean values for traits under irrigated and upland conditions is shown in online Supplementary Table S6.

Yield performance and trait association under low temperature conditions

ANOVA of traits for rice genotypes evaluated under timely and late sown conditions is shown in online Supplementary Table S7. Out of 257 rice entries tested for low temperature stress, 36 entries failed to flower under late sown conditions. Local organic cultivars recorded tallest mean plant height of 84.16 cm against 66.94 cm and 48.45 cm recorded for released varieties and breeding lines, respectively. Local cultivars also recorded highest grain yield per panicle, highest yield per hill and yield per m^2. Mean values of rice entries under different genotype groups are shown in Table 1. Although released varieties had a relatively high number of panicles per m^2 than the local cultivars and breeding lines but the former showed better grain yield under low temperature conditions. Plant height showed significantly positive correlation with panicles per m^2 and grain yield per m^2, however the magnitude of association was low (online Supplementary Table S8). Grain yield per m^2 was significantly associated with yield per hill (0.96), yield per panicle (0.84), panicles per m^2 (0.25) and plant height (0.14).However, yield per panicle showed negative correlation with panicles per m^2.

Table 1. Summary statistics of landraces, released varieties and advance lines evaluated under low temperature stress at Gangtok location

Summary statistics	Landraces	Released varieties	Advance breeding lines
Plant height (cm)	Mean: 86.03	Mean: 66.94	Mean: 48.45
	S.E[1]: 3.16	S.E: 1.74	S.E: 0.59
	SD[2]: 13.78	SD: 15.03	SD: 6.73
	Min[3]: 52.15	Min: 40.1	Min: 28.5
	Max[4]: 102.78	Max: 102.13	Max: 75.8
Panicles/m^2	Mean: 353.46	Mean: 404.89	Mean: 320.10
	S.E: 25.97	S.E: 13.81	S.E: 7.42
	SD: 116.17	SD: 118.79	SD: 84.02
	Min: 226.41	Min: 165	Min: 133
	Max: 598.75	Max: 742.5	Max: 530
Yield per panicle (g)	Mean: 0.77	Mean: 0.55	Mean: 0.60
	S.E: 0.08	S.E: 0.04	S.E: 0.04
	SD: 0.40	SD: 0.40	SD: 0.51
	Min: 0.14	Min: 0.05	Min: 0
	Max: 1.52	Max: 2.20	Max: 3.75
Yield/m^2 (g)	Mean: 251.94	Mean: 205.39	Mean: 187.23
	S.E: 27.66	S.E: 15.14	S.E: 13.61
	SD: 123.72	SD: 130.32	SD: 154.0
	Min: 47.26	Min: 20.83	Min: 0
	Max: 575	Max: 587.5	Max: 1033.33

[1]Standard Error
[2]Standard Deviation
[3]Minimum
[4]Maximum

Relative yield performance and trait association under timely and late sown conditions

Under timely sown conditions organic cultivars recorded an average grain yield of 227.98 g/m^2 as compared to 411.33 g per m^2 in conventional varieties (Table 2).

ANOVA for both irrigated and upland environment is shown in online Supplementary Tables S9a and S9b. However under late sown conditions the mean grain yield of organic cultivars was 17.28% (236.75 g/m^2) higher than the conventional varieties (195.82 g/m^2). Organic cultivars attained higher plant height (111.74 cm) as compared to conventional varieties (82.30 cm). Yield per plant in organic cultivars remained unaffected under late sown conditions coinciding with low temperature while the same reduced significantly in HYVs (54.18%). Local cultivar Chirakey Dhan (8.21 g/plant) showed superiority over check VL Dhan 86 (5.93 g) under late sown conditions, whereas among conventional varieties HPU-741 (8.39 g) and VL Dhan-82 (6.30 g) showed superiority over the check. None of the

Table 2. Summary statistics of local organic and conventional rice genotypes under timely and late sown conditions at Gangtok location

	Organic		Conventional/HYVs	
	Timely	Late	Timely	Late
Plant height (cm)	Mean: 111.73	Mean: 87.55	Mean: 82.30	Mean: 66.19
	SE: 5.98	SE: 5.39	SE: 2.24	SE: 2.16
	SD: 18.91	SD: 17.07	SD: 15.53	SD: 15.01
	Min: 70.5	Min: 48.60	Min: 44.8	Min: 40.1
	Max.: 126.32	Max.: 102.78	Max.: 106.59	Max.: 96.70
Yield/hill (g)	Mean: 3.03	Mean: 3.59	Mean: 5.48	Mean: 2.74
	SE: 0.76	SE: 0.81	SE: 0.43	SE: 0.24
	SD: 2.42	SD: 2.31	SD: 3.01	SD: 1.67
	Min: 0.23	Min: 0.71	Min: 0.73	Min: 0.89
	Max.: 8.25	Max.: 8.21	Max.: 15.52	Max.: 8.39
Yield/m^2 (g)	Mean: 227.97	Mean: 236.75	Mean: 411.12	Mean: 195.91
	SE: 57.45	SE: 47.52	SE: 32.65	SE: 16.78
	SD: 181.69	SD: 150.29	SD: 226.21	SD: 116.29
	Min: 17.5	Min: 50	Min: 55.46	Min: 62.5
	Max.: 619.21	Max.: 575	Max.: 1164.53	Max.: 587.5

https://doi.org/10.1017/S1479262123000576 Published online by Cambridge University Press

Table 3. ANOVA for yield parameters of twenty one rice varieties under organic conditions for two years

Source of variation	df	Grain yield	Plant height	Days to flowering	Panicles/m^2
Variety	10	3,187,563.51***	938.30***	135.49**	8820.46***
Year	2	3,065,453.30*	470.75	101.11	67,645.41***
Block	2	348,839.41	234.76	17.53	2038.45
Variety × Year	20	1,797,227.64*	420.01*	50.28	2012.45
R^2		0.54	0.54	0.58	0.66

***Significant at $P = 0.001$, **: 0.01 and *0.05.

organic cultivar surpassed best check for grain yield under timely sown conditions.

System × variety interaction of traits affecting grain yield

ANOVA for yield parameters of rice varieties under organic conditions is shown in Table 3. Varieties differ significantly for grain yield, plant height, days to flowering and panicles/m^2. The variety × year interaction was significant for grain yield and plant height while no interactions were observed for days to flowering and panicles per m^2. ANOVA for yield and its related traits under type of farming (organic/conventional) is shown in Table 4. ANOVA for system type showed significance of varieties for all the four traits whereas variety × system interactions were significant for plant height and days to flowering whereas no interactions was observed for grain yield and panicles/m^2. Correlation coefficient of rice varieties under organic and conventional systems under irrigated and upland ecology is shown in online Supplementary Table S10. Grain yield under all four environments showed significantly positive association with panicles per m^2. Plant height showed negative correlation with days to flowering under organic upland conditions (−0.50) while the same showed positive correlation (0.38) under conventional upland conditions. Grain yield under organic upland conditions showed positive (0.30) association with plant height. Panicles per m^2 were positively associated with days to flowering under organic upland conditions (0.27).

Discussion

Sub-optimal weather conditions and low soil fertility create a less productive environment for gaining high grain yields in rice under organic system in hills. This is also evident from the mean grain yield of 3249 kg/ha recorded in coordinated trials over years at organic site (Gangtok) as compared to 4905 kg/ha recorded in other hill locations following conventional practices. Majority of the rice cultivars of Sikkim performed poorly under rainfed upland conditions in which significant reduction recorded in plant height, tillers per plant, panicle length and test weight which ultimately led to decrease in grain yield. Rice cultivars of Sikkim are adapted to optimum soil moisture conditions due to ample rainfall received in the region during *kharif* season and rarely face moisture deficit. Moreover rice cultivation is done under irrigated transplanted conditions and rarely under direct seeded upland system. Cultivars Taichung and Pahelo Dalle yielded well under both irrigated and upland conditions which need to be further tested at different organic locations for assessing stability in performance under moisture deficit conditions. Following this approach two rice varieties Sikkim Dhan-1 and Sikkim Dhan-3 were released in 2020 for organic conditions of Sikkim with high and stable grain yield under both irrigated and rainfed-upland ecology (https://icar.org.in/content/state-variety-release-committee-releases-new-crop-varieties-icar-nofri-sikkim).

Under timely sown conditions, HYVs yielded significantly higher than the local cultivars signifying role of improved genotypes in gaining high productivity under low input conditions. However, the superior agronomic performance of HYVs could not be realized under late sown conditions encountered by low temperature where local cultivars exhibited superiority in grain yield. This emphasized the importance of local cultivars which otherwise are low yielding than HYVs possess such specific traits which needs to be combined with HYVs for better resilience. Among cultivars Chirakey Dhan and Dharmali displayed higher grain filling and grain yield under late sown conditions coinciding with low temperature are promising genotypes which require further validation for trait superiority at multi-locations. Non-significant interaction between varieties and system of cultivation ruled out specific adaptation of rice varieties to organic systems which performed more or less at par under both organic and conventional system. However varietal variations over years were significant for grain yield which is evident of the heterogenous conditions of the organic farms. Among traits, number of panicles per m^2 came out as an important yield deciding trait under both

Table 4. ANOVA for yield traits under type of farming (organic/conventional)

Source of variation	df	Grain yield	Plant height	Days to flowering	Panicles/m^2
Variety	54	2,013,143.6**	255.084**	203.28***	3016.94
Type	2	15,050,460.9***	20,073.98***	2485.17***	1191.33
Variety × Type	78	1,309,972.7	141.43*	39.05***	2900.73
Error	28				
R^2		0.91	0.97	0.98	0.81

***Significant at $P = 0.001$, **: 0.01 and *0.05.

irrigated and upland conditions in organic systems. Along with it plant height too influenced grain yield significantly under organic upland conditions.

Diminishing area under rice cultivation in hills due to conversion of paddy fields to other remunerative organic cash crops pose a serious challenge for attaining self-sufficiency and yield sustainability of rice in hill states. Local cultivars/farmer's varieties dominate traditional farming systems which guarantee grain yields even under hostile environmental conditions. Enhancing acreage under rice HYVs particularly for timely sown conditions under organic management shall be prioritized for increasing productivity. Genetic improvement of rice for organic systems must be in line with the local needs of the farmers. Local rice cultivars of Sikkim need to be evaluated for specific biotic and abiotic stress tolerance and then shall be deployed in rice improvement programme as donor for specific traits in background of elite or high yielding genotypes. Significant variability still exists in local organic rice cultivars which require simple selection followed by generation advancement. Testing conventional rice varieties under organic conditions shall continue to be the best strategy for selection of best performing lines until varieties bred specifically for organic systems are available. Genotypes performing well under both irrigated and rainfed upland environments shall be prioritized under organic conditions. One of the limitations of our study was that we could not conduct trials under conventional inorganic conditions along with organic trials as chemical based fertilizers/inputs are prohibited for agricultural use in Sikkim. Nevertheless, our study substantiates the performance under both organic and conventional environment at locations outside the study site.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1479262123000576.

Acknowledgements. The authors express deep sense of gratitude to The Director, ICAR Research Complex for NEH Region, Umiam, Meghalaya for providing necessary facilities for carrying out the study. We are thankful to The Director ICAR-IIRR, Hyderabad for providing trials for the study. Authors extend special thanks to farmers and officials of the State Agriculture Department of Sikkim for their kind cooperation and support.

References

Choudhury B, Khan ML and Dayanandan S (2013) Genetic structure and diversity of indigenous rice (*Oryza sativa* L.) varieties in the Eastern Himalayan region of North East India. *SpringerPlus*, **2**, 228. https://dx.doi.org/10.1186%2F2193-1801-2-228

Choudhury DR, Singh N, Singh AK, Kumar S, Srinivasan K, Tyagi RK, Ahmad A, Singh NK and Singh R (2014) Analysis of genetic diversity and population structure of rice germplasm from North-Eastern region of India and development of a core germplasm set. *PLoS ONE* **9**, 11. https://doi.org/10.1371/journal.pone.0113094

Crespo-Herrera LA and Ortiz R (2015) Plant breeding for organic agriculture: something new? *Agriculture and Food Security* **4**, 25. https://doi.org/10.1186/s40066-015-0045-1

de Ponti T, Rijk B and van Ittersum MK (2012) The crop yield gap between organic and conventional agriculture. *Agricultural Systems* **108**, 1–9.

Dubey K (2016) *Evaluation of rice varieties for organic farming* (MSc Thesis JNKVV). 80p. Jabalpur. Available at http://krishikosh.egranth.ac.in/handle/1/5810001159

Eyhorn F, Muller A, Reganold JP, Frison E, Herren HR, Luttikholt L, Mueller A, Sanders J, Scialabba N EL-Hage, Seufert V and Smith P (2019) Sustainability in global agriculture driven by organic farming. *Nature* **2**, 253–255.

Federer WT (1956) Augmented (or hoonuiaku) designs. *Hawaiian Planters' Record* LV, 191–208.

Gabriel D, Sait SM, Hodgson JA, Schmutz U, Kunin WE and Benton TG (2010) Scale matters: the impact of organic farming on biodiversity at different spatial scales. *Ecology Letters* **13**, 858–869.

Gabriel D, Sait SM, Kunin WE and Benton TG (2013) Food production vs. biodiversity: comparing organic and conventional agriculture. *Journal of Applied Ecology* **50**, 355–364.

Hore DK (2005) Rice diversity collection, conservation and management in North Eastern India. *Genetic Resources and Crop Evolution* **52**, 1129–1140.

Huang L, Jun Y, Yang J, Zhang R, Bai Y, Sun C and Zhuang H (2016) Relationships between yield, quality and nitrogen uptake of organically grown rice varieties. *Pedosphere* **26**, 85–97.

Husaini AM and Sofi NR (2018) Rice biodiversity in cold hill zones of Kashmir Himalayas and conservation of its landraces. In Grillo O (ed.), *Rediscovery of Landraces as A Resource for Future*. Intech Open, pp. 39–58. https://doi.org/10.5772/intechopen.69576

Imam J, Alam S, Mandal NP, Variar M and Shukla P (2013) Molecular screening for identification of blast resistance genes in North East and Eastern Indian rice germplasm (*Oryza sativa* L.) with PCR based markers. *Euphytica* **196**, 199–211.

Kirchmann H, Bergstrom L, Katterer T, Andren O and Andersson R (2008) Can organic crop production feed the world? In Kirchmann H and Bergstrom L (eds), *Organic Crop Production-Ambitions and Limitations*. Dordrecht, The Netherlands: Springer, pp. 39–72.

Krauss M, Berner A, Perrochet F, Frei R, Niggli U and Mader P (2020) Enhanced soil quality with reduced tillage and solid manures in organic farming- a synthesis of 15 years. *Scientific Reports* **10**, 4403.

Kumari KV and Shanmugam PM (2020) Evaluation of rice (*Oryza sativa*) varieties suitable for organic farming. *Indian Journal of Agricultural Research* **54**, 71–76.

Liu H, Meng J, Bo W, Cheng Da, Li Y, Guo L, Li C, Zheng Y, Liu M, Ning T, Wu G, Yu X, Feng, S, Wuyun T, Li J, Li L, Zeng Y, Liu Shi V and Jiang G (2016) Biodiversity management of organic farming enhances agricultural sustainability. *Scientific Reports* **6**, 23816.

Mandi SK, Sarkar S and Goswami SB (2018) Evaluation of organically grown rice varieties foe their seed yield and quality in the lower Indo-Gangetic plains. *Environment and Ecology* **36**, 817–822.

Manjunatha GA, Vanaja T, Naik J, Kumar Anil AS and Vasudevan NR (2016) Identification of rice genotypes best suited for the development of organic varieties and identification of current varieties best suited for organic farming. *Journal of Organics* **3**, 16–24.

Mehta PS, Ojha SN, Negi KS, Rayal A and Tyagi RK (2014) On-farm status of rice (*Oryza sativa* L.) genetic resources in Garhwal Himalaya of Uttarakhand, India. *Genetic Resources and Crop Evolution* **61**, 1279–1294.

Muneret L, Mitchell M, Seufert V, Aviron S, Djoudi El A, Petillon J, Plantegenest M, Thiery D and Rusch A (2018) Evidence that organic farming promotes pest control. *Nature Sustainability* **1**, 361–368.

Murphy KM, Campbell KG, Lyon SR and Jones SS (2007) Evidence of varietal adaptation to organic farming systems. *Field Crops Research* **102**, 172–177.

Najeeb S, Mahender A, Anandan A, Hussain W, Li Z and Ali J (2021) Genetics and breeding of low-temperature stress tolerance in rice. In Ali J and Wani SH (eds), *Rice Improvement*. Cham: Springer, pp. 221–280.

Ngachan SV, Mohanty AK and Pattanayak A (2014) Status Paper on Rice in North East India. Available at http://www.rkmp.co.in/sites/default/files/ris/rice-statewise/Status%20 Paper % 20 on % 2 0 Rice%20in%20North%20East%20India.pdf

Nuijten E, Messmer M and Lammerts van Bueren E (2017) Concepts and strategies of organic plant breeding in light of novel breeding techniques. *Sustainability* **9**, 18. https://doi.org/10.3390/su9010018

Ponisio LC, M'Gonigle LK, Mace KC, Palomino J, de Valpine P and Kremen C (2015) Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B* **282**, 20141396.

Rana JC, Negi KS, Wani SA, Saxena S, Pradheep K, Kak A, Pareek SK and Sofi P (2009) Genetic resources of rice in the Western Himalayan region of India: current status. *Genetic Resources and Crop Evolution* **56**, 963–973.

Roy S, Banerjee A, Mawkhlieng B, Misra AK, Pattanayak A, Harish GD, Singh SK, Ngachan SV and Bansal KC (2015) Genetic diversity and population structure in aromatic and quality rice (*Oryza sativa* L.) landraces from North Eastern India. *PLoS ONE* **10**. https://doi.org/10.1371/journal.pone.0129607

Seufert V, Ramankutty N and Foley J (2012) Comparing the yields of organic and conventional agriculture. *Nature* **485**, 229–232.

Singh DK, Gupta S, Nanda G, Sharma Y, Singh VV and Bisarya D (2017) Evaluation of rice varieties for yield under organic farming in Tarai region of Uttarakhand, India. *International Journal of Current Microbiology and Applied Sciences* **6**, 734–738.

Tuck SL, Winqvist C, Mota F, Ahnstrom J, Turnbull LA and Bengtsson J (2014) Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. *Journal of Applied Ecology* **51**, 746–755.

Umakanth B, Vishalakshi B, Sathish Kumar P, Rama Devi SJS, Bhadana VP, Senguttuvel P, Kumar S, Sharma SK, Sharma PK, Prasad MS and Madhav MS (2017) Diverse rice landraces of North-East India enables the identification of novel genetic resources for Magnaporthe resistance. *Frontiers in Plant Science* **8**. https://doi.org/10.3389/fpls.2017.01500

Vanaja T, Neema VP, Mammootty KP, Balakrishnan PC and Jayaprakash N (2017) A high yielding organic rice variety suited for coastal saline and non-saline fields:'Ezhome-2'. *Journal of Organics* **4**, 21–28.

van Bueren L, Goldringer E, Scholten O and Ostegard H (2007) Plant breeding for organic and sustainable, low- input agriculture: dealing with genotype-environment interactions. In: Book of Abstracts, Proceedings of Eucarpia Symposium of Working Group Organic Plant Breeding, Wageningen, The Netherlands, p. 4.

van Bueren ETL, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C and Messmer MM (2011) The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: a review, NJAS. *Wageningen Journal of Life Sciences* **58**, 193–205.