

DATASET ARTICLE • **OPEN ACCESS**

Unbalanced panel data from wheat fields in India: supplemental irrigation and food system sustainability

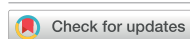
To cite this article: A Ajay *et al* 2026 *Environ. Res.: Food Syst.* **3** 014502

View the [article online](#) for updates and enhancements.

You may also like

- [Using satellite data to identify the causes of and potential solutions for yield gaps in India's Wheat Belt](#)
M Jain, Balwinder Singh, A A K Srivastava et al.
- [The Effect of a Number of Irrigations on the Growth and Yield Traits of Three Varieties of Bread Wheat \(*Triticum aestivum* L.\)](#)
Enas Ismail Mohammed
- [Response of Three Wheat Genotypes to Irrigation with Different Salinity Levels in Gypsiferous Soils](#)
H S M Al-Fahdawy, M I K Al-Fahdawy, O I Al-Fahdawy et al.

ENVIRONMENTAL RESEARCH FOOD SYSTEMS



DATASET ARTICLE

OPEN ACCESS

RECEIVED

4 August 2025

REVISED

3 February 2026

ACCEPTED FOR PUBLICATION

12 February 2026

PUBLISHED

20 February 2026

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Unbalanced panel data from wheat fields in India: supplemental irrigation and food system sustainability

A Ajay^{1,2,*} , M Singh² , S Patra² , S P Poonia², A Pundir², P Kumar², D K Singh², A Kumar², M Ignatius², H Ranjan², S Sherpa³ , R K Malik², V Kumar⁴, A J McDonald⁵ and A M Laing²

¹ Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale), Germany

² International Maize and Wheat Improvement Center (CIMMYT), New Delhi, India

³ International Maize and Wheat Improvement Center (CIMMYT), Kathmandu, Nepal

⁴ International Rice Research Institute (IRRI), Los Banos, The Philippines

⁵ School of Integrative Plant Science, Cornell University, Ithaca, NY, United States of America

* Author to whom any correspondence should be addressed.

E-mail: a.ajay@cgiar.org

Keywords: additional irrigation, Bihar, field trial, grain yield, India, wheat

Supplementary material for this article is available [online](#)

Abstract

Wheat (*Triticum aestivum* L.) is a major winter season crop and a primary source of food and income for farmers in eastern India. Inadequate irrigation of wheat in this area limits its production potential. Our study evaluates the significance of one additional irrigation (supplemental) to wheat. The study presents large-scale multi-location agronomic field/on-farm trial data of supplemental irrigation conducted over six consecutive years in eastern India. The extensive agricultural experiment covered 1810 farmers' fields spanning five agro-climatic zones. The objective was to validate the contribution of supplemental irrigation applied to wheat at the grain-filling stage in supporting wheat grain yield. The on-farm experiment was structured as a split-plot design, with the additional irrigation (Treatment) randomly assigned to sub-plots. All field locations were geo-tagged and grain yields were recorded using physical crop cuts. The data was carefully curated, anonymized, and released through a Dataverse portal making it reusable and interoperable. The dataset is invaluable in understanding sustainable wheat production in regions where wheat is inadequately irrigated.

1. Background

Irrigation is a crucial farm input for crops to produce optimal yield or to achieve potential yield, especially under water stress conditions. In recent years, its role as a potential climate adaptation solution to alleviate heat stress has also come to forefronts (Dubey *et al* 2020). Smallholder farmers in eastern India, with limited financial resources, inadequately irrigate wheat, leading to yield penalties. Recommended number of irrigations for winter wheat in India is 4–5 often matching with its critical growth stages (Coventry *et al* 2011). In contrast, majority of farmers in eastern India, on an average, apply three irrigations. A survey of wheat farmers at a landscape level in this area had revealed that only 5% of farmers apply either four or more irrigations (Ajay *et al* 2021). Irrigation at the grain-filling stage (hereafter termed supplemental) is considered to play an important role in raising wheat yield, most likely by safeguarding the crop from extreme heat during maturity (referred to as terminal heat stress) (Zaveri and Lobell 2019). Our agronomic experiment was conducted to generate robust field-level data-based evidence around the contributory role of supplemental irrigation in wheat.

Research conducted on experimental farms, primarily by research institutes and agricultural universities, has demonstrated beneficial connections between irrigation and wheat yields (Ullah *et al* 2022). In the context of rising atmospheric temperature caused by climate change, the role of irrigation has become even more crucial. Some studies have quantified the importance of irrigation for the projected climate scenarios (Trnka *et al* 2004, Asseng *et al* 2013). The contribution of irrigation in yield

improvement and also towards climate resilience is undebatable (Nangia and Oweis 2017). However, how accurately these results represent and replicate in real-world (farmer's field) settings is often questionable (Kool *et al* 2020). Our large-scale field experiment is an attempt to ensure that research findings represent farmer's fields more accurately. The resulting policies from such datasets become more realistic and impactful.

The current irrigation system for wheat in smallholder-dominated environment of eastern India largely depends on groundwater extracted through diesel-powered pumps (Rajkhowa 2024). The system leads to high and uneven irrigation costs (Foster *et al* 2021). Beyond yield penalties, this dependence exacerbates profit inefficiencies in wheat production by increasing input costs and constraining optimal water use (Ajay *et al* 2025). Rising diesel prices and declining groundwater tables further limit timely and adequate water application. While increasing irrigation frequency is important, prioritizing irrigations that generate the highest marginal yield is critical. Such decisions ultimately hinge on the availability of reliable, field-representative data assets. The kind of dataset generated through our study in terms of its nature and stature, so far, is not available in India. Therefore, the study is significant in bridging the evidence gap between controlled experimental research and real-world production conditions.

The primary objective of this study was to generate data-driven evidence from real-world wheat production environments by evaluating the effect of supplemental irrigation applied at the grain-filling stage of wheat on yield. One limitation of the study was that, despite being conducted over six years with strong farmer participation, not all farmers were able to participate consistently across all seasons due to various constraints. As a result, the sample size was unbalanced, although continuous efforts were made to recruit new farmers to keep it sufficiently large for adequate representation.

Apart from yield, the dataset comprises a wide array of variables ($K = 62$) related to farm inputs and crop production practices, covering the entire crop cycle from planting to harvesting (Singh *et al* 2023). The richness in terms of length and breadth makes the dataset particularly valuable for research in crop modeling and related disciplines. Moreover, the inclusion of field-specific geocoordinates significantly enhances its useability, enabling integration with geospatial variables such as climate and soil properties.

2. Data deposition

The data is publicly available at CIMMYT Research Data & Software Repository Network, a Dataverse portal (<https://data.cimmyt.org/>) through a dedicated page of institutional network namely Cereal Systems Initiative for South Asia (CSISA) Research Data. It has a persistent digital identifier and has no access restriction (<https://hdl.handle.net/11529/10548945>). The page includes actual dataset as a CSV file, a HTML file presenting data structure, a metadata sheet, a map showing experimental sites, and a spreadsheet describing all variables in the data. It is freely downloadable for lawful use and complies with FAIR (Findable, Accessible, Interoperable, Reusable) data principles. 'Creative Commons CC0 Public Domain Dedication' serves as the default license for all datasets on this portal unless an explicit license choice or custom 'terms of use' are mentioned. However, good scientific practices expect proper credit via citation available on the Dataverse portal.

2.1. Method

2.1.1. Experimental sites

The agronomic trial was conducted in the eastern Indian state of Bihar and adjoining areas of Uttar Pradesh (figure 1). The climate is predominantly subtropical with hot summers, a monsoon season, and mild winters (November to March), when wheat is cultivated (Shah *et al* 2013). Soil varies from fertile alluvial plains in the north to relatively less fertile upland soils in the south. The study area represents five agro-climatic zones and includes 47 districts, characterized by slightly differing climatic conditions and soil types (Tefaye *et al* 2017). Districts were selected in each agro-climatic zone based on the intensity of wheat cultivation, ensuring spatial distribution while maintaining logistical feasibility. Within each selected district, farmers were identified using a 'first met—first agreed' approach, contingent on their willingness to adhere to research protocols. In each village, between two and four farmers were selected. Each experimental plot was confirmed only after verifying that it met the minimum size requirement (> 4000 sq meters) and had reliable access to irrigation.

2.2. Experiment design

The trial employed a split-plot design in which each selected field was divided into two equal-sized plots, designated as control and treatment (Altman and Krzywinski 2015). Supplemental irrigation was randomly assigned to one of the plots, while all other inputs and agronomic practices were kept consistent

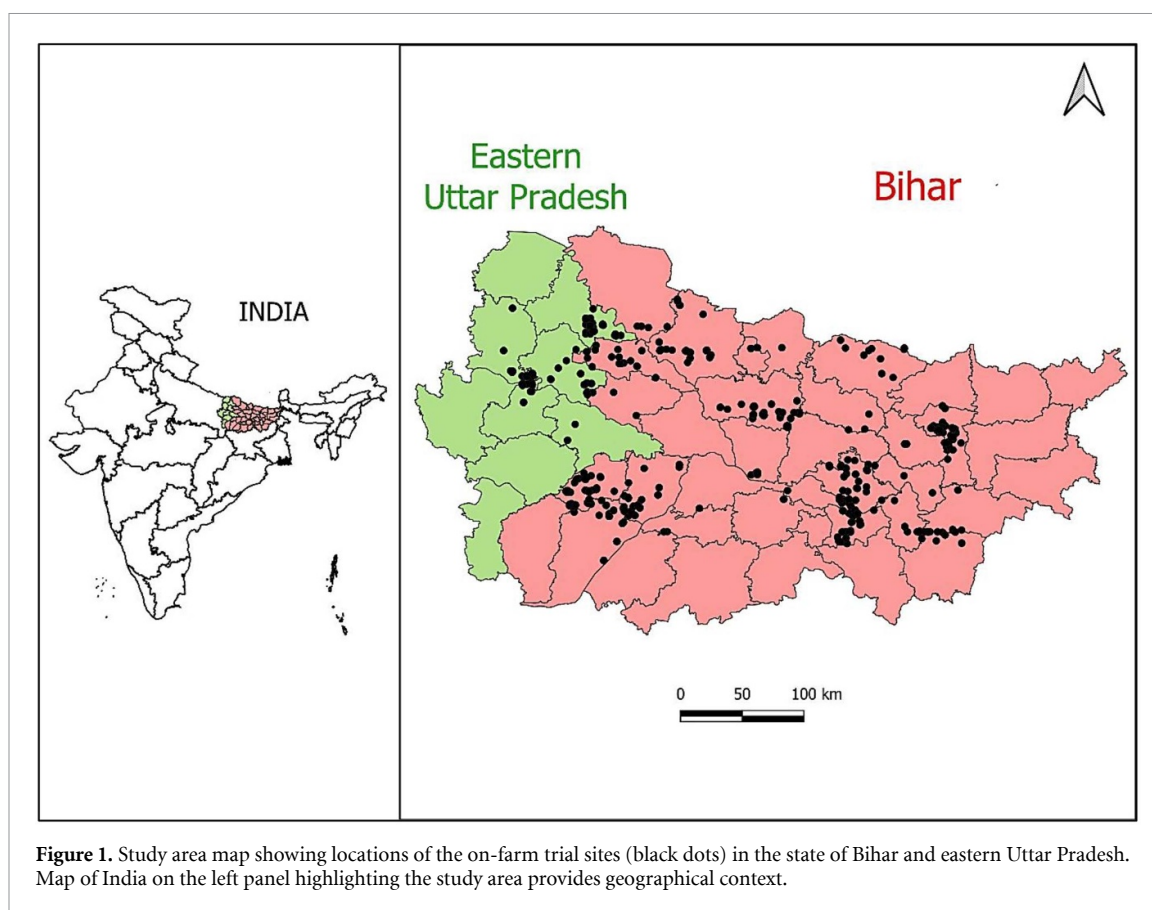


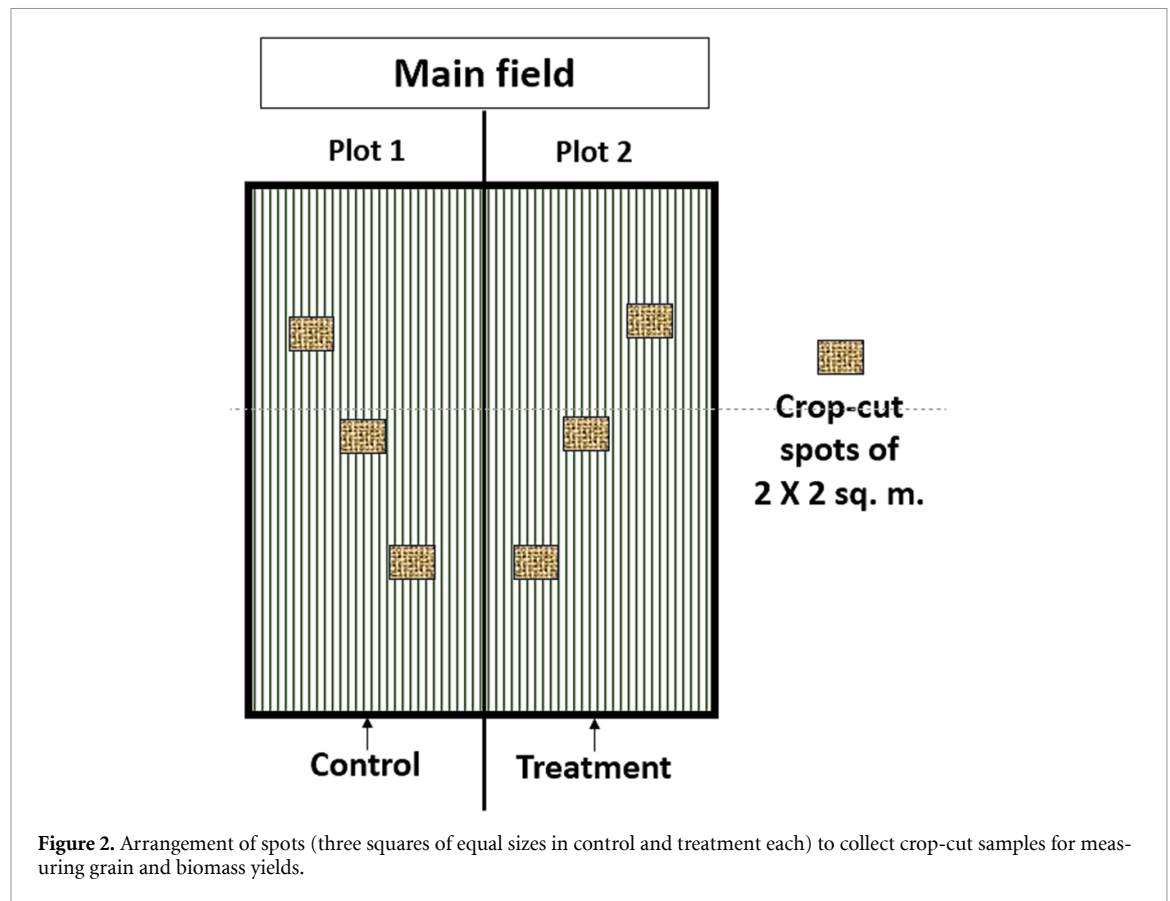
Table 1. Trial design depicting the arrangement of main plot and sub-plots into control and treatment plots with increasing number of irrigations.

Irrigation numbers	Main plot	Sub-plot (Control: farmer's practice; treatment: otherwise)
One irrigation	Zero tillage	Farmer's practice One additional irrigation at grain-filling stage
	Conventional tillage	Farmer's practice Additional irrigation at grain-filling stage
Two irrigations	Zero tillage	Farmer's practice One additional irrigation at grain-filling stage
	Conventional tillage	Farmer's practice Additional irrigation at grain-filling stage
Three irrigations	Zero tillage	Farmer's practice One additional irrigation at grain-filling stage
	Conventional tillage	Farmer's practice Additional irrigation at grain-filling stage
Four irrigations	Zero tillage	Farmer's practice One additional irrigation at grain-filling stage
	Conventional tillage	Farmer's practice Additional irrigation at grain-filling stage

across both plots. For example, if the control plot received two irrigations, the treatment plot received the same two irrigations plus a supplemental irrigation at the grain-filling stage. The main fields were categorized based on the tillage method used for wheat planting—either zero tillage or conventional tillage (table 1). In zero tillage, wheat is sown without prior land preparation, whereas in conventional tillage, the field is ploughed multiple times before broadcasting wheat seeds (Erenstein *et al* 2008).

2.3. Data collection

Data collection was conducted in two rounds under the supervision of a dedicated agronomist in each agro-climatic zone. The first round took place approximately two weeks before harvest and focused



on gathering information related to inputs and management practices. Using a standardized template, trained field technicians who had been involved since the trial's inception, collected data on seed type, planting date, fertilizer application, irrigation, weed management, and other agronomic details, including geo-coordinates of the fields. The second round was conducted at crop maturity to record grain and biomass yields. A common instrument was applied over space and years of experiment.

From each field, crop yields were recorded using physical crop cuts from six spots—three in the control plot and three in the treatment plot. Each sampling spot measured four square meters (2×2 m) and was aligned diagonally within the plot (figure 2). The first spot was located at the center, while the other two were placed diagonally opposite from the center, ensuring they were at least 10 m inside the plot boundary. Harvesting was carried out at full crop maturity. After separately threshing the samples from each plot, grain weights (kg) were measured for respective spots using electronic weighing scales to minimize enumeration errors.

The same procedure was followed to measure and calculate biomass yield. In this case, the entire harvested crop (including grain and straw) was bundled and weighed. The recorded weights, measured in kilograms, were then converted to tons per hectare for each plot. The conversion process took the average weight of three spots, converted kg to ton and four-square meters to hectare (ha). The mathematical formula used in conversion is given below:

$$Y_{\text{ton/ha}} = \left\{ \frac{(S1 + S2 + S3)}{3} \right\} \times \frac{1}{1000} \times \frac{10000}{4}$$

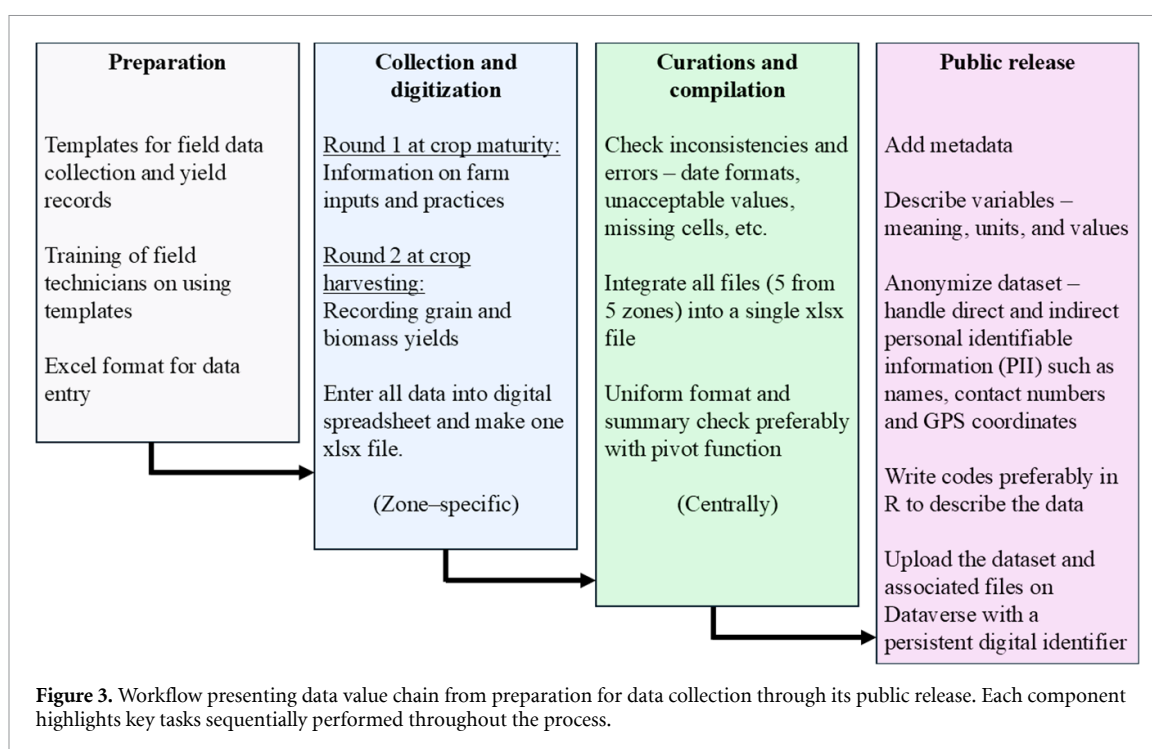
where,

$Y_{\text{ton/ha}}$ = Yield of either above ground biomass or grain in ton per hectare

S1, S2, & S3 = Weights of either above ground biomass or grain recorded in kilogram from three sampling spots

2.4. Compilation and dataset preparation

In each of the five zones, the designated agronomist entered the data into a standardized spreadsheet and submitted it to the central data processing unit. At the central unit, the data was compiled, carefully curated, anonymized, and prepared for public release (figure 3). During this process, the dataset was thoroughly checked for inconsistencies and data entry errors. Any missing values were verified with



the respective field teams before finalizing the records. All files underwent a rigorous annual quality control process before being merged into a unified dataset. Once compiled, the data was harmonized and formatted to improve clarity and usability.

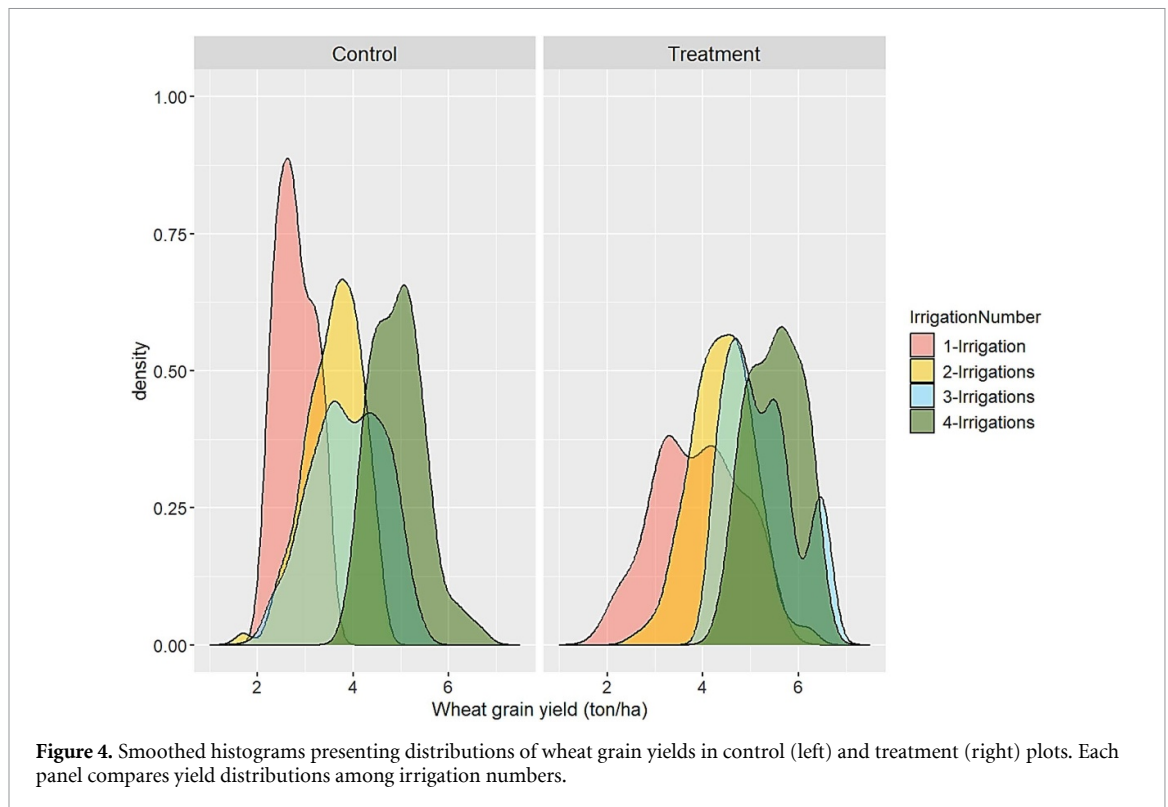
Data managers adhered to the FAIR data principles in preparing the dataset for public release. A comprehensive metadata sheet was developed to provide detailed information of the dataset, and a separate sheet to clearly define and describe each variable. All personally identifiable information either direct or indirect (farmer names, addresses, contact numbers, and geo-coordinates) was carefully anonymized in accordance with the open data policy. The finalized dataset, along with its associated metadata, was uploaded to the Dataverse portal with no access restrictions, ensuring open and equitable access to all users.

3. Data description

The dataset comprises observations from 1810 farmers' fields growing bread wheat and includes 63 variables. Approximately 80% of the fields were located in eight districts of Bihar, with the remaining fields in two districts of eastern Uttar Pradesh. The experiment began during the 2016–17 wheat season (with planting in November 2016 and harvesting in May 2017) and continued through the 2021–22 season. The dataset consisted of information on cultivars, sowing time, irrigation, fertilizer management, weed control methods, and previous crops grown on this field. Regarding field types, nearly 60% of the fields were planted using zero tillage techniques. Overall, wheat grain yields ranged from 2.0 to slightly over 6.0 tons per hectare. The check was performed to verify that grain yields are distributed within a valid range. Several additional data descriptions in the form of graphs have been presented to visually assess the distribution of output (grain yield) variable with respect to treatment. A set of density plots comparing wheat grain yields across different irrigation levels under control and treatment groups is presented (figure 4).

Both control and treatment plots showed a general trend of higher yields with more irrigations. Plots in the treatment group shifted rightward for each irrigation level, indicating higher yields than their control counterparts.

A set of comparative boxplots of wheat grain yield by number of irrigations is presented separately for both zero and conventional types (figure 5). It was evident that treatment plots had higher yields than control plots across all irrigation levels in both zero and conventional tillage fields. The yield variability (spread of the box and whiskers) was wider at lower irrigation levels and becomes tighter as irrigation increases, suggesting more consistent yields at higher irrigation intensity. We found that zero and

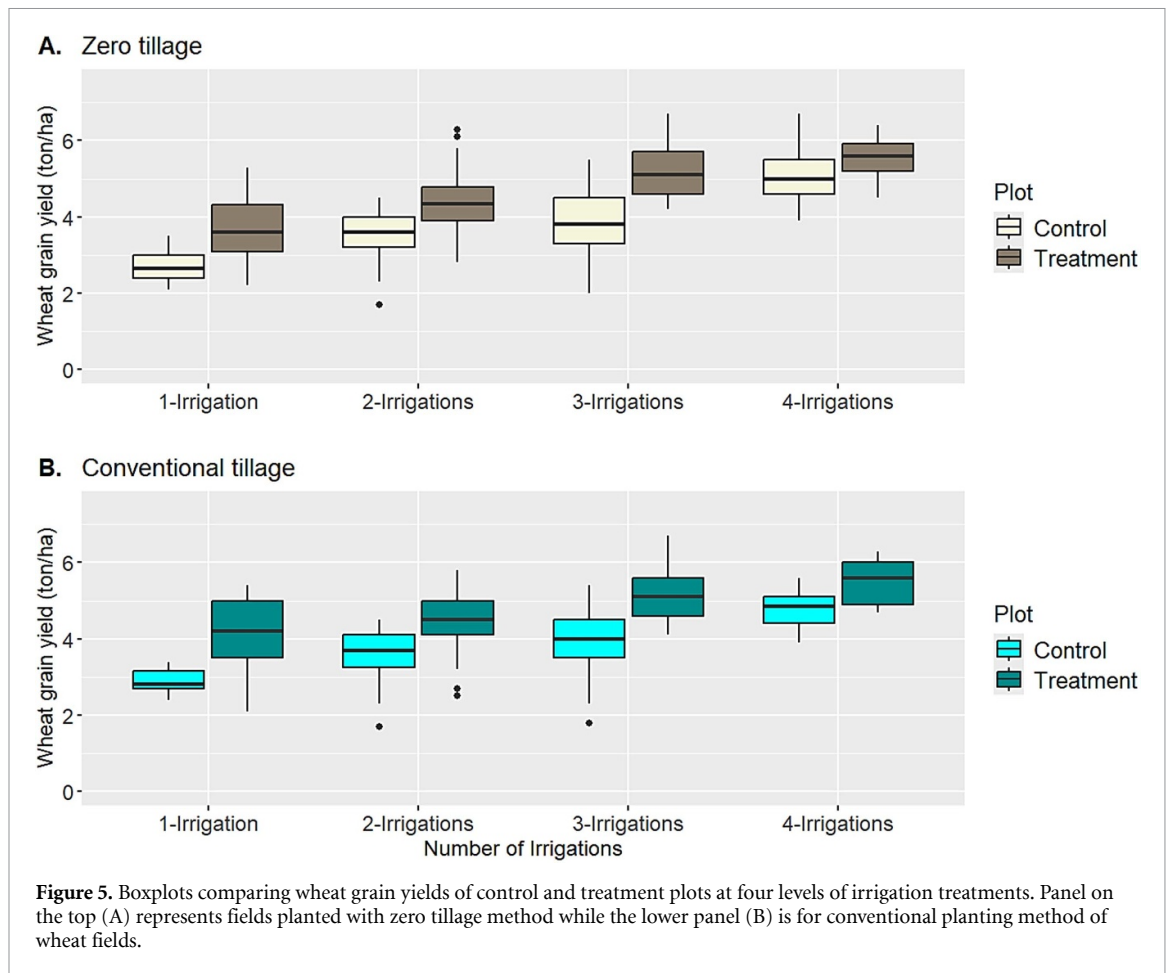


conventional tillage both respond positively to supplemental irrigation. These visualizations were essential for showcasing that the yield values fell within expected ranges and to confirm that the treatment (supplemental irrigation) had a positive, meaningful and measurable effects.

The dataset provides quantifiable insights into how irrigation practices influence wheat yield and, by extension, food system sustainability in the eastern India. The wide yield variations observed across irrigation numbers highlights substantial scope for closing yield gaps through improved irrigation practices.

The yield distributions in figure 4 demonstrate that increasing irrigation frequency shifts wheat grain yields toward higher values while narrowing the spread under the treatment condition. Treatment plots show a consistent higher average yield, along with reduced yield variability. This dual effect of higher means and lower dispersion highlights irrigation optimization as a critical lever not only for boosting production but also for stabilizing outcomes across fields. Under the scenario of increasing climate variability posing higher heat stress conditions for wheat, such reductions in yield risk are central to food system resilience and sustainability (Dubey *et al* 2026). It thereby extends support to a more reliable wheat production, predictable market supply, and reduce vulnerability of farmers' incomes (Tadesse *et al* 2017). Moreover, the clear response of wheat yields to irrigation frequency underscores the potential for targeted irrigation interventions to deliver measurable gains without excessive intensification of wheat-based food systems.

The comparative yield gains under zero and conventional tillage methods of wheat establishment in figure 5 further underscores the added advantage of zero-tillage as a complementary practice. Zero-tillage fields under treatment group consistently achieve narrower interquartile ranges than their control counterparts, indicating greater yield stability. This effect was highly robust with four irrigations. Notably, the yield response to supplemental irrigation suggests that conservation-based land preparation enhance the benefits of improved irrigation management (Humphreys *et al* 2011). This synergy is particularly important for sustainable food system transformation, as zero-tillage reduces soil disturbance, conserves moisture resulting in better soil structure over time (Aryal *et al* 2015). Overall, these findings highlight that supplemental irrigation, when coupled with zero tillage, reinforces effective strategies for advancing wheat-based food system productivity and sustainability. Together, they offer a scalable pathway to enhance and stabilize wheat yields while contributing to the long-term food security in the region.



4. Machine readable R script

A script in R (version—2023.12.1) software has been provided that reads the dataset and summarizes it (Wickham 2011). The codes generate data dimensionality, structure, its varied distributions over time and space while presenting visualizations for comparing control and treatment plots. The data can be directly accessed from: <https://hdl.handle.net/11529/10548945>

```
## Set working directory to link data
setwd('insert your file location—all elements separated by\\')

## Uploading data
data <- read.csv('CSISA_IND_Irrigation_Trial_Data_2017-22_Final.csv')

## Install libraries
library(knitr)
library(dplyr)
library(ggplot2)
library(crosstable)
library(summarytools)

## Data dimension
dim(data)

## Variables in the dataset
names(data)

## Sample distribution in the study area
table(data$State)
```

```
## Sample distribution segregated by states and respective district
xtabs(~ State + District, data)

## Sample distribution segregated by years and respective district
xtabs(~ District + Year, data)

## Sample distribution by wheat establishment methods
frequency<-table(data$CropEstablishment)
pie(frequency)

## Histogram of wheat yields
hist(data$GrainYield, main = 'Yield histogram', xlab = 'Wheat grain yield (ton/ha',
xlim = c(0,10))

## Yield distribution as density plots in control and treatment plots
cols <- c('#F76D5E', '#FFcc00', '#72D8FF', '#336600')
ggplot(data, aes(x = GrainYield, fill = IrrigationNumber)) +
  facet_wrap('Plot') +
  geom_density(alpha = 0.5) +
  scale_fill_manual(values = cols) + xlim(1,7.5) + ylim(0,1) +
  labs(x = 'Wheat grain yield (ton/ha)') +
  theme(axis.text.x = element_text(size = 12),
        axis.text.y = element_text(size = 12),
        axis.title.x = element_text(size = 13),
        axis.title.y = element_text(size = 13)) +
  theme(strip.text = element_text(size = 14)) +
  theme(legend.title = element_text(size = 12),
        legend.text = element_text(size = 12))

## Treatment effects separately in zero and conventional tillage
# Sub-set data of zero tillage fields
IRZT <- data[which(IR$CropEstablishment=='ZT'),]
p1 <- ggplot(IRZT, aes(x = IrrigationNumber, GrainYield, fill = Plot))
z <- p1 + geom_boxplot() +
  labs(title = 'Zero tillage') +
  labs(x = " ", y = 'Wheat grain yield (ton/ha)')+
  ylim(0,7.5) + scale_fill_manual(values = c('beige','bisque4')) +
  theme(axis.text = element_text(size = 12)) +
  theme(axis.title = element_text(size = 12)) +
  theme(legend.title = element_text(size = 13),
        legend.text = element_text(size = 13)) +
  theme(plot.title = element_text(size = 14))
# Sub-set data of conventional tillage fields
IRCT <- data[which(IR$CropEstablishment=='CT'),]
p2 <- ggplot(IRCT, aes(x = IrrigationNumber, GrainYield, fill = Plot))
c <- p2 + geom_boxplot() +
  labs(title = 'Conventional tillage') +
  labs(x = 'Number of Irrigations', y = 'Wheat grain yield (ton/ha)')+
  ylim(0,7.5) + scale_fill_manual(values = c('cyan1','cyan4')) +
  theme(axis.text = element_text(size = 12)) +
  theme(axis.title = element_text(size = 12)) +
  theme(legend.title = element_text(size = 13),
        legend.text = element_text(size = 13)) +
  theme(plot.title = element_text(size = 14))
# Combine both the plots horizontally
figure <- ggarrange(z, c, labels = c('A.', 'B.'), nrow = 2)
figure
#### End.
```

Acknowledgment

This field experiment was funded by the Bill and Melinda Gates Foundation (BMGF) through Grant Numbers OPP-1133205 and INV-029117. We are grateful to *Krishi Vigyan Kendra* (KVK) of 10 districts included in our study for their support in monitoring the field trial.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://hdl.handle.net/11529/10548945>.

Supplemental Irrigation in Wheat available at <http://doi.org/10.1088/2976-601X/ae4519/data1>.

Conflict of interest

The authors declare no competing interests.

Author contributions

A Ajay  0000-0001-7502-6166

Conceptualization (supporting), Formal analysis (lead), Visualization (lead), Writing – original draft (lead)

M Singh

Conceptualization (supporting), Data curation (lead), Validation (lead)

S Patra  0009-0001-1644-9916

Data curation (lead), Validation (supporting)

S P Poonia

Conceptualization (supporting), Supervision (lead)

A Pundir

Conceptualization (supporting), Project administration (lead)

P Kumar

Conceptualization (supporting), Project administration (lead)

D K Singh

Conceptualization (supporting), Project administration (lead)

A Kumar

Conceptualization (supporting), Investigation (supporting), Project administration (lead)

M Ignatius

Investigation (lead), Project administration (lead)

H Ranjan

Software (lead), Validation (supporting)

S Sherpa  0000-0003-1758-3399

Conceptualization (lead), Methodology (supporting), Supervision (supporting)

R K Malik

Conceptualization (lead), Methodology (supporting), Resources (lead)

V Kumar

Conceptualization (lead), Funding acquisition (lead), Methodology (lead)

A J McDonald  0000-0002-2660-3470

Conceptualization (lead), Funding acquisition (lead), Methodology (lead), Resources (supporting)

A M Laing

Funding acquisition (supporting), Resources (lead), Supervision (lead)

References

- Ajay A, Craufurd P and Sharma S 2021 Landscape diagnostic survey data of wheat production practices and yield in eastern India *Open Data J. Agric. Res.* **7** 20–26
- Ajay A, Mkondwiwa M, Urfels A and Müller D 2025 Delineating profit gaps in rice and wheat production: evidence from India's economically marginalized region *Agric. Food Econ.* **13** 93
- Altman N and Krzywinski M 2015 Points of significance: split plot design *Nat. Methods* **12** 165
- Aryal J P, Sapkota T B, Jat M L and Bishnoi D K 2015 On-farm economic and environmental impact of zero-tillage wheat: a case of North-West India *Exp. Agric.* **51** 1–16
- Asseng S, Ewert F, Rosenzweig C, Jones J W, Hatfield J L, Ruane A C and Wolf J 2013 Uncertainty in simulating wheat yields under climate change *Nat. Clim. Change* **3** 827–32
- Coventry D R, Yadav A, Poswal R S, Sharma R K, Gupta R K, Chhokar R S and Cummins J A 2011 Irrigation and nitrogen scheduling as a requirement for optimising wheat yield and quality in Haryana, India *Field Crops Res.* **123** 80–88
- Dubey R, Kumar S, Ajay A, Prakash V, Das A, Kumar S and Dwivedi S K 2026 Interactive effects of drought and heat on morphophysiological components and yield of wheat (*Triticum aestivum* L.) in India *J. Agron. Crop Sci.* **212** e70148
- Dubey R, Pathak H, Chakrabarti B, Singh S, Gupta D K and Harit R C 2020 Impact of terminal heat stress on wheat yield in India and options for adaptation *Agric. Syst.* **181** 102826
- Erenstein O, Farooq U, Malik R K and Sharif M 2008 On-farm impacts of zero tillage wheat in South Asia's rice–wheat systems *Field Crops Res.* **105** 240–52
- Foster T, Adhikari R, Adhikari S, Justice S, Tiwari B, Urfels A and Krupnik T J 2021 Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains *Agric. Water Manage.* **256** 107070
- Humphreys E, Eberbach P L, Katupitiya A and Kukal S S 2011 Growth, yield and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule *Field Crops Res.* **121** 209–25
- Kool H, Andersson J A and Giller K E 2020 Reproducibility and external validity of on-farm experimental research in Africa *Exp. Agric.* **56** 587–607
- Nangia V and Oweis T 2017 Supplemental irrigation: a promising climate-resilience practice for sustainable dryland agriculture *Innovations in Dryland Agriculture* (Springer) pp 549–64
- Rajkhowa P 2024 From subsistence to market-oriented farming: the role of groundwater irrigation in smallholder agriculture in eastern India *Food Secur.* **16** 353–69
- Shah D B, Pandya M R, Trivedi H J and Jani A R 2013 Estimating minimum and maximum air temperature using MODIS data over Indo-Gangetic Plain *J. Earth Syst. Sci.* **122** 1593–605
- Singh M et al 2023 Large On-farm Trial Data to Assess the Effect of Additional Irrigation on Yields of Wheat Established through Zero and Conventional Tillage Methods in Eastern India (Version 3) [Data Set] (CIMMYT Research Data & Software Repository Network) (available at: <https://hdl.handle.net/11529/10548945>)
- Tadesse W, Halila H, Jamal M, El-Hanafi S, Assefa S, Oweis T and Baum M 2017 Role of sustainable wheat production to ensure food security in the CWANA region *J. Exp. Biol. Agric. Sci.* **5** S15–S32
- Tesfaye K, Aggarwal P K, Mequanint F, Shirsath P B, Stirling C M, Khatri-Chhetri A and Rahut D B 2017 Climate variability and change in Bihar, India: challenges and opportunities for sustainable crop production *Sustainability* **9** 1998
- Trnka M, Dubrovský M, Semerádova D and Žalud Z 2004 Projections of uncertainties in climate change scenarios into expected winter wheat yields *Theor. Appl. Climatol.* **77** 229–49
- Ullah A, Nadeem F, Nawaz A, Siddique K H and Farooq M 2022 Heat stress effects on the reproductive physiology and yield of wheat *J. Agron. Crop Sci.* **208** 1–17
- Wickham H 2011 ggplot2 *Wiley interdisciplinary reviews: computational statistics* **3** 180–5
- Zaveri E B and B. Lobell D 2019 The role of irrigation in changing wheat yields and heat sensitivity in India *Nat. Commun.* **10** 4144