

Potash fertilization demo plot trials in onion across Western and Central Maharashtra

Results from 35 pair-wise plot trials across the region

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Image source: (Potash for life 2014)

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1. Abstract

Onion (*Allium cepa* L.) is one of India's most important and culturally significant vegetable crops, cultivated across nearly all states. Its versatility, storability and high domestic demand make it central to both diets and rural incomes. Despite established fertilizer recommendations for nitrogen (N) and phosphorus (P), potassium (K) has received comparatively little attention in onion production (Kumara, Mansur et al. 2018). This study evaluated the effect of muriate of potash (MOP; KCl) on onion yield and profitability across 35 field trials conducted during the *rabi* seasons of 2018-19 and 2019-20 in western and central Maharashtra. Each site comprised paired plots with identical management differing only in the inclusion of MOP.

The application of muriate of potash (MOP) significantly increased onion yield across all the sites, with an average absolute gain of 423 kg ha⁻¹ (13.7% relative increase). Profitability analysis indicated a strong economic return, with an average benefit-to-cost ratio of 5.0. Variation between years and drainage classes reflected the influence of soil-water dynamics on baseline yield levels and the yield gap available for potassium response. In 2018-19 (hot and dry conditions), imperfectly drained soils retained more moisture and achieved higher control yields, leaving a smaller yield gap and a weaker response to muriate of potash (MOP). In contrast, during 2019-20 (cooler and wetter conditions), baseline yields declined, particularly in imperfectly drained soils, resulting in larger yield increases and a stronger muriate of potash (MOP) response. District-level effects were not significant, indicating that local soil and moisture conditions, rather than geography, governed MOP performance.

Overall, the results confirmed that potassium as a limiting nutrient in many onion-growing soils of Maharashtra and demonstrated that MOP application can improve both productivity and profitability when adapted to local moisture conditions.

(Keywords: *Allium cepa* L.; Cost-benefit analysis; Fertilizer regimes; Maharashtra; MOP.)

2. Introduction

2.1. Crop significance

Onion (*Allium cepa L.*) is the most widely cultivated vegetable species of the genus *Allium*, grown in over 150 countries worldwide. In 2023, the global harvested area of onion exceeded 7 million ha, producing approximately 116 million Mg, with an average yield of 16 Mg ha⁻¹ (FAO 2025). The leading onion-producing countries are India, China, Egypt and the United States, followed by Turkey, Bangladesh and Iran. India surpassed China as the world's largest producer in 2021, with a total output of about 26 million Mg.

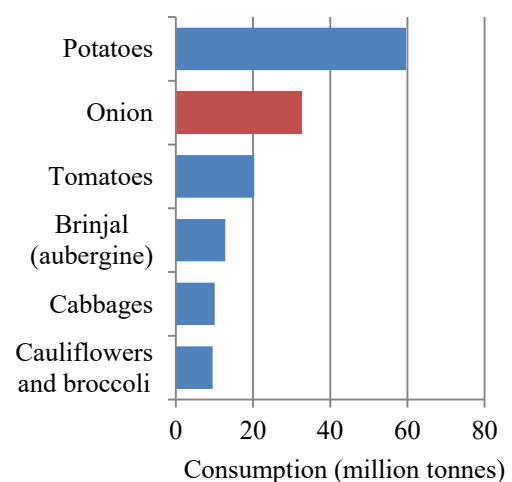
India exported just over 2.5 million tonnes of onions in 2023 and imported a nominal 20.5 thousand tonnes, resulting in an annual consumption of approximately 27.7 million tonnes. Among India's major vegetable crops, onion ranks below potato in overall consumption, but above tomato, brinjal (aubergine), cabbage and cauliflower/broccoli (Figure 1). Onion has been a staple food in India for millennia, being mentioned in food literature and medical discourses as far back as the 6th century BC-celebrated for its health benefits, versatility in cooking and its ability to be preserved in times of shortage.

Today, sweet forms are consumed in salads and for making pickles, spicier and more pungent onions for stews and soups and red onions for use in fast-cooking stir-fries where their colour and distinctive flavour can be retained. There are also Indian medicinal traditions using onion including relief of chest congestion, lowering of blood pressure and antiseptic properties.

Onion is therefore one of the most important and culturally significant vegetable crops in India.

By value, onion comprises INR 268 billion which is 2.0% of India's total arable agricultural GDP or 4.5% of horticultural GDP. It is in the top five contributors to gross agricultural GDP after mango, banana, potato and tomato; consumed raw or dried to produce dehydrated and granulated products; the latter of which is frequently exported to neighbouring partner countries.

Figure 1. Comparison of vegetable consumption in India by type (2023).



The above figure compares domestic consumption of different vegetables in volume terms (FAO 2025). Onion ranks second after potato.

Owing to its importance in Indian culture, volatility in onion prices has been a recurring political issue throughout India's recent history. The first example of prevailing high prices concerned its use as a critical lever in Indira Gandhi's win in the 1980 general election (Wigg 1980). Steep price rises are also thought to have brought down the government of Delhi in 1998 (Jadhav and Bhardwaj 2018), and shortages in 2010 resulted in a ban of exports following heavy rain.

Figure 2. Photo of onions ready for harvest



Photo: Onion tops turning down indicating readiness for harvest. Source: (Schwartz 2013).

Similar export bans have occurred more recently; however, the resulting domestic oversupply led to a price crash, with farmers in some areas unable to recover the production costs. The long-term solution is undoubtedly the development of more reliable supply chains; however, another important factor is improving productivity through optimized agronomic practices.

2.2. Onion cultivation and supply

Onion production is widespread across India with a total of 15 major producing states. Cultivation takes place in both *kharif* (monsoon) and *rabi* (winter) seasons. *Kharif* planting is more common accompanied by thorough irrigation to maximize final sizes of bulbs. Just over half of India's onion crop comes from the *kharif* crop across the country meeting supply needs until the end of May; after which stored *rabi* (winter) crops grown in Maharashtra, Madhya Pradesh, Rajasthan and Gujarat meet demand for the rest of the year.

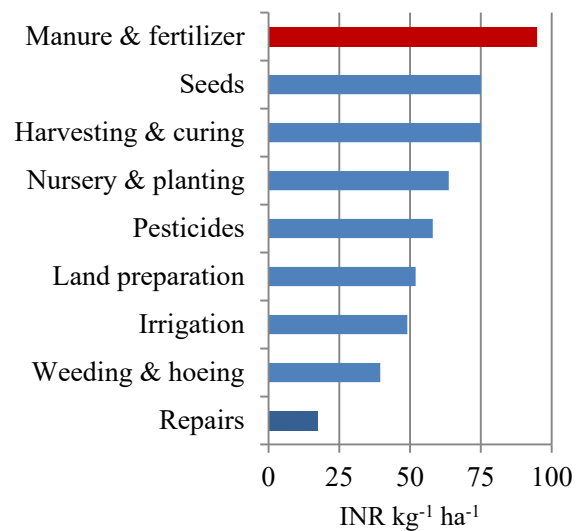
Figure 3. Onion harvesting schedules in different Indian states

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rabi states	Andhra Pradesh			Yellow	Green		Green	Yellow	Yellow	Green	Green	Green	Yellow
	Karnataka				Green	Green	Green	Yellow	Yellow	Green	Green	Yellow	
	Himachal Pradesh					Green	Green			Yellow	Yellow		
Kharif states	Madhya Pradesh			Green	Green	Yellow							
	Maharashtra					Yellow	Green	Yellow					
	West Bengal					Yellow	Green	Yellow					

The above chart shows harvesting schedules in India's "rabi" and "kharif" states. Yellow indicates light harvesting and green peak harvesting.

Bulbs can be planted during April-May for *kharif* crops and October-November for *rabi*, taking 80-150 days to reach harvest (Figure 3); readiness for harvest is indicated by the leafy green tops turning yellow and bending downward (Figure 2). Onion grows well in red loam through to black soils assuming drainage is adequate. It prefers a range of moderate temperatures and a mild season but will grow in tropical and subtropical climates. As a hardy crop it will also tolerate some light frost, especially at early growth stages.

Figure 4. Comparison of variable production costs for onion growing in India



The above figure compares variable costs of onion production (India). Manures and fertilizers are the highest variable cost at over INR 90 kg⁻¹ ha⁻¹ (Barakade, Lokhande et al. 2011).

Soil pH should be maintained within the range of 5.5-6.5; above 6.5, available micronutrients such as zinc, manganese and iron decrease and below 5.5 deficiencies of molybdenum and magnesium can occur (Haifa 2018). With zinc being the most prevalent micronutrient constraint in India (Varma, Kakra et al. 2019), pH levels toward the lower end of this range are preferable.

Fertilization and irrigation are important for quality and yield of onion in India. Fertilizers and manure combined are the largest variable farm-related cost in the cultivation of onion in India (after transportation and marketing), comprising INR 90,000 ha⁻¹ (Figure 4) or 18 % (Barakade, Lokhande et al. 2011). Sources of N are important for general formative growth, K for translocation of photosynthates, root development, formation of carbohydrates, and water regulation.

3. Objectives

The trials had two main objectives, and a third ancillary objective:

- **Objective 1:** To demonstrate to farmers the increased yield and profitability achievable through the application of MOP in addition to conventional use of DAP, urea and manure.

- Objective 2: To evaluate the response of onion to MOP under recommended fertilizer regimes on potassium-deficient soils.
- Objective 3: To determine whether any secondary factors influenced yield.

4. Materials and methods

4.1. Experimental setup

The 35 trials were conducted in nine districts across the western and central regions of Maharashtra, India (Ahmednagar, Aurangabad, Buldana, Jalna, Nashik, Pune, Sangli, Satara and Solapur; Figure 6). Soils at the trial sites were classified mainly as Vertic Cambisols, Ferric Luvisols or Calcaric Gleysols. Other soil characteristics are summarized in Figure 7 and Table 2.

Onion crops were established during the *rabi* seasons of 2018-19 and 2019-20. Sowing dates ranged from 13 October to 17 December in 2018-19 and from 10 October to 9 January in 2019-20. On each farm, a pair of equally sized onion plots was laid side by side; one control plot receiving a standard fertilizer program and one treatment plot receiving the same program plus MOP. Plot sizes within each pair were identical; however, sizes between the pairs varied from 0.1 to 0.4 ha. All recommended agronomic practices were followed.

4.2. Treatments

Farmyard manure was applied prior to sowing at rates ranging from 9 to 12 t ha⁻¹, depending on local practice (Table 1). NPK fertilization was applied at rates of 100 kg N ha⁻¹, 50 kg P₂O₅ ha⁻¹ and 50 kg K₂O ha⁻¹ respectively. Urea and di-ammonium phosphate (DAP) served as the nitrogen and phosphorus sources, and muriate of potash (MOP; KCl) was used as the sole potassium source in the +K plots.

Table 1. Fertilizer and manure application rates for control and +K treatments in the onion field trials

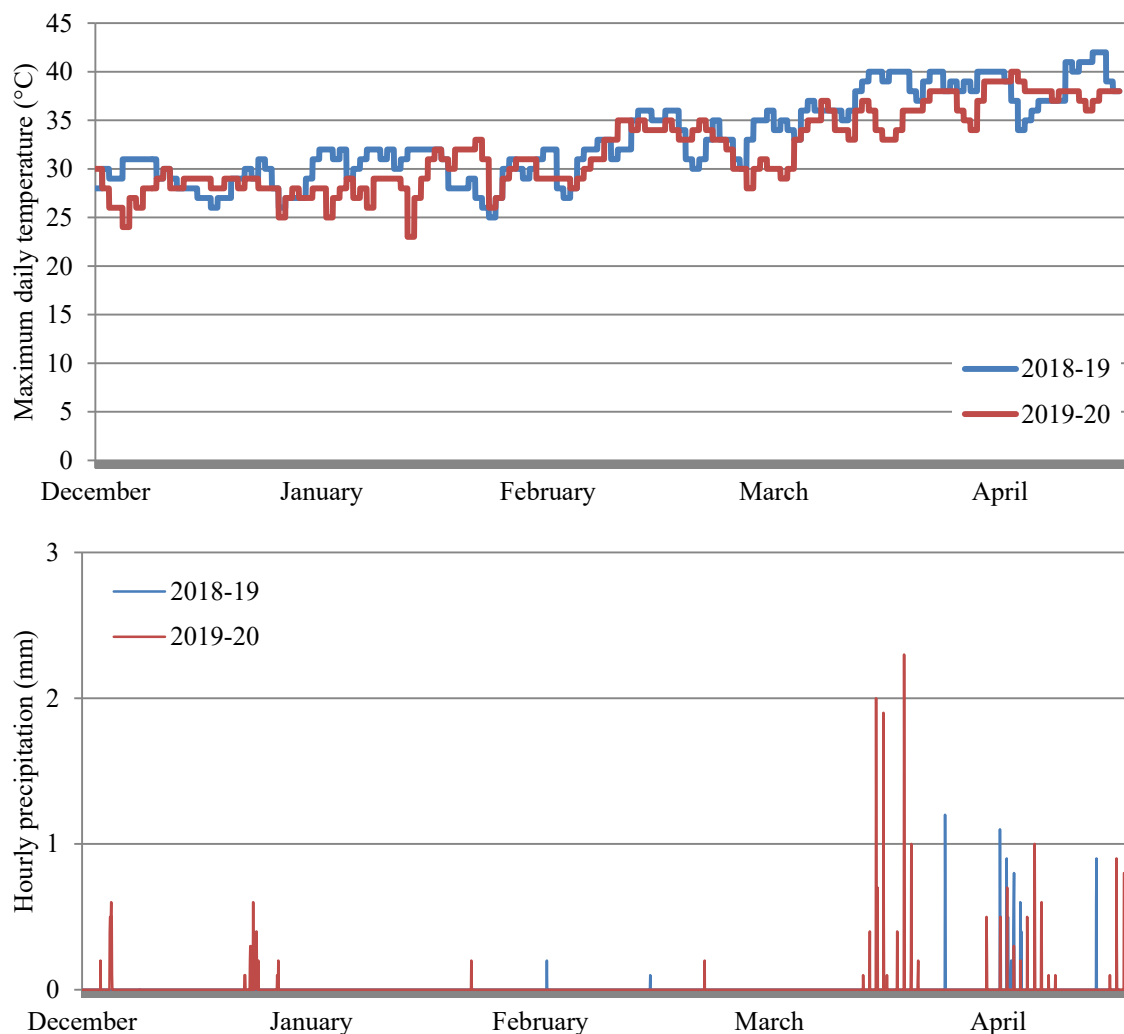
Fertilizer source	kg ha ⁻¹		kg plot ⁻¹ *	
	Control	+ K	Control	+ K
N (from urea + DAP)	100		20	
P ₂ O ₅ (from DAP)	50		10	
K ₂ O (from MOP)	0	50	0	10
Manure	10*		1.8	

The above table shows the fertilizer and manure application rates for control and +K treatments in the onion field trials. Values presented with an asterisk (*) represent medians across all plots.

4.3. Climate variables

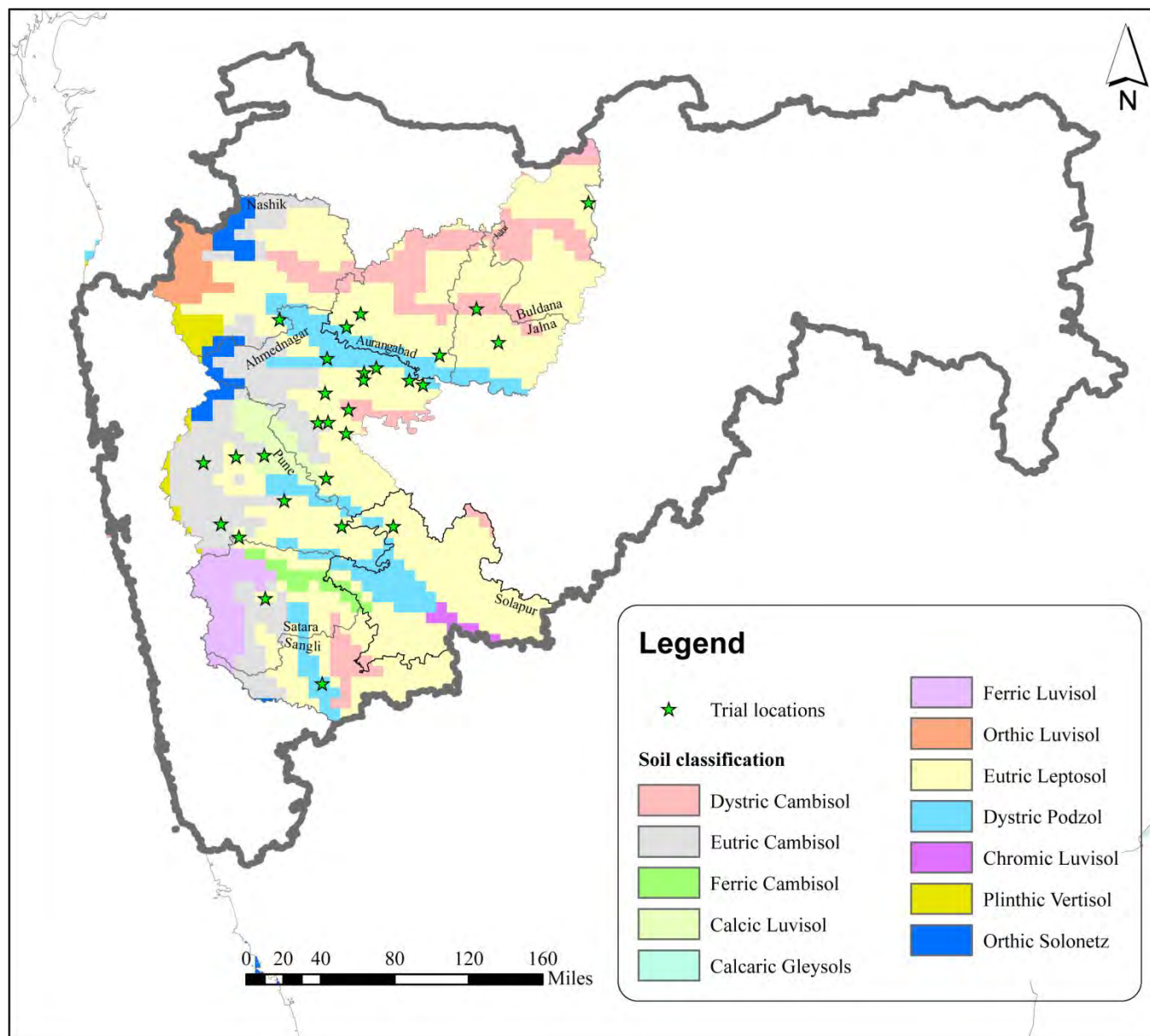
Figure 5 shows the maximum daily temperature (°C) and hourly precipitation (mm) at the center of the study area during the *rabi* season for both trial years (2018-19 and 2019-20). The data indicate a clear climatic difference between the two years. In 2018-19, maximum daily temperatures were consistently higher-on average about 2 °C above those in 2019-20 throughout the *rabi* season-while rainfall was much lower, with a total of 11 mm over the five-month period compared with 32 mm in 2019-20. Overall, the 2018-19 *rabi* season was markedly warmer and drier than the following year.

Figure 5. Climate variables recorded at the centre of the study area (Northern Pune) during onion growth (a) Maximum hourly temperatures, and (b) Hourly precipitation



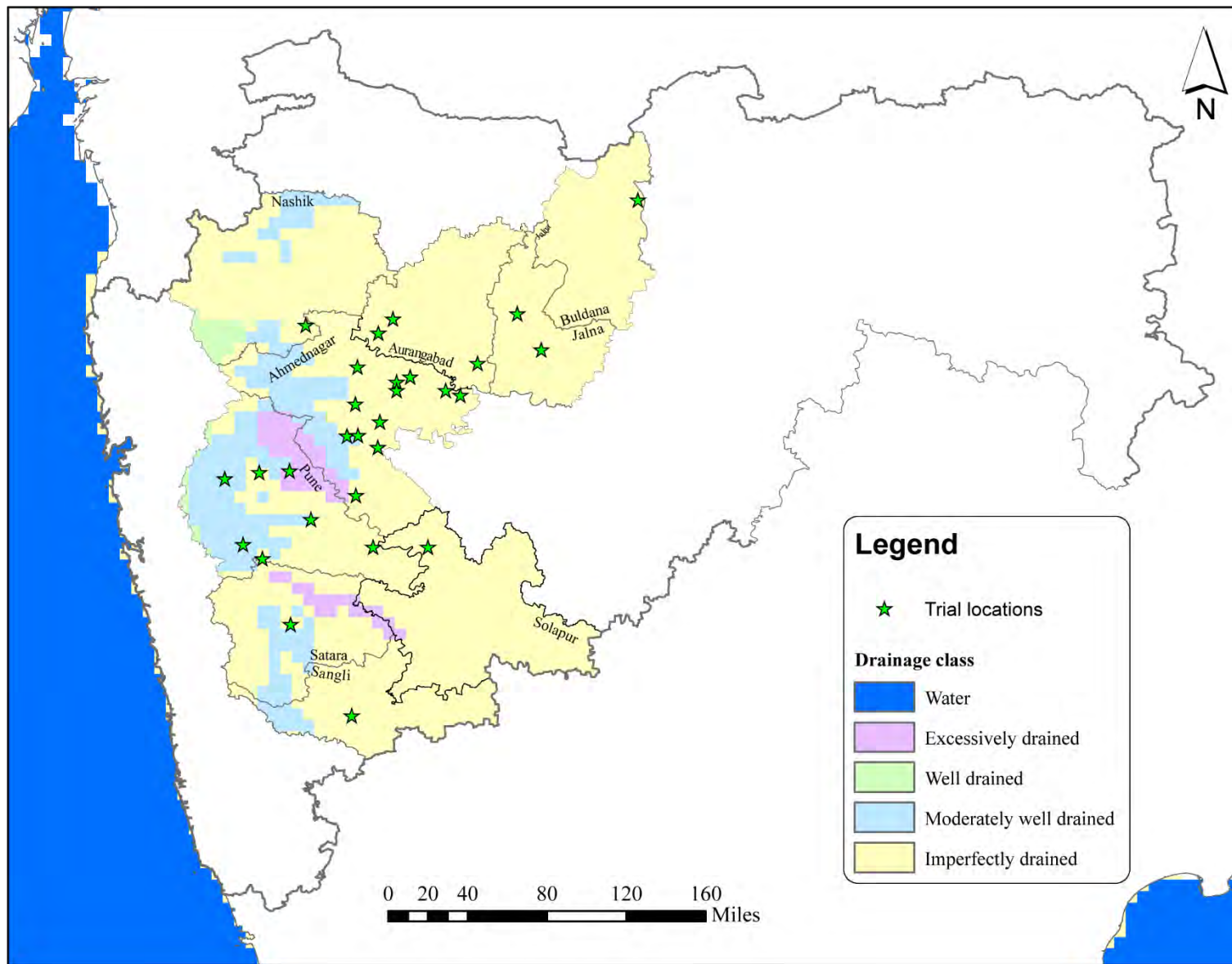
The above figures show (a) the maximum daily temperature and (b) the hourly precipitation recorded in the northern part of Pune district, at the center of the study area during *rabi* season of the two trial years. The maximum daily temperatures were noticeably higher in 2018-19: an average of two degrees over the five months. Precipitation was noticeably lower in 2018-19, totalling just 11 mm compared to 32 mm in 2019-20. Data: (Deshmukh 2023)

Figure 6. Map of the study area showing trial locations and soil classifications



The map to the left shows the trial study area extending from the foothills of the Western Ghats eastward into central Maharashtra. Trial locations are marked with green stars, with associated districts shown and labeled. The map base shows soil classifications within the study area according to the colours in the legend. Data: (Batjes 2008, Hijman 2020).

Figure 7. Map of the study area showing trial locations and soil drainage class



The map to the left shows the trial study area extending from the foothills of the Western Ghats eastward into central Maharashtra. Trial locations are marked with green stars, with associated districts shown and labelled. The map base shows the soil drainage classes within the study area according to the colours in the legend. Data: (Batjes 2008, Hijman 2020).

Table 2. Trial soil characteristics

State	District	No. of trials	Soil classifications	Soil drainage	K status	% Clay (Texture)	pH
Maharashtra	Ahmednagar	16	Eutric Leptosol, Eutric Cambisol, Dystric Podzol, Dystric Cambisol	Moderately well-drained to imperfectly drained	Low to High	10-35% (Light to Medium)	Normal, Slightly alkaline
Maharashtra	Buldana	1	Eutric Leptosol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline
Maharashtra	Aurangabad	4	Eutric Leptosol, Dystric Podzol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline
Maharashtra	Jalna	2	Eutric Leptosol, Dystric Cambisol	Imperfectly drained	High	10-60+% (Light to Heavy)	Slightly alkaline
Maharashtra	Nashik	1	Dystric Podzol	Imperfectly drained	Medium	10-20% (Light)	Slightly alkaline
Maharashtra	Pune	8	Eutric Leptosol, Eutric Cambisol, Calcic Luvisol	Excessively well-drained, moderately well-drained to imperfectly drained	Medium to High	10-35% (Light to Medium)	Normal, Slightly alkaline
Maharashtra	Sangli	1	Dystric Podzol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline
Maharashtra	Satara	1	Eutric Leptosol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline
Maharashtra	Solapur	1	Eutric Leptosol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline

The above table details trial soil characteristics by district, including number of trials per district, soil classifications, soil drainage class, K status, % clay (texture) and pH. These characteristics were used in investigating variations in yield levels and MOP response, in combination with climatic data. Data: (Soil and Land Use Survey of India 2025)

4.4. Statistical tests

The following statistical tools were applied for the analyses described in the text:

- Tukey's test was used to identify potential outliers in the dataset; none were detected.
- A pairwise t-test was performed to assess whether differences in mean yield between the 35 control plots and the 35 + K plots were attributable to MOP application rather than random variation.
- Analysis of variance (ANOVA) was used to determine which independent variables significantly affected yield metrics, followed by a Holm-adjusted Bonferroni correction to identify differences among groups. Independent variables tested included district, location (longitude and latitude), soil parameters (soil classification, K status, clay content/soil type, drainage class, soil organic carbon (SOC) class, and pH), year, growing duration, and manure dose.
- Multiple regression analyses were subsequently performed to examine relationships among the significant variables identified in the ANOVA and to explore interaction effects.

4.5. Calculation of profitability

Profitability of each trial was calculated as benefit-cost ratio using Equation 1. This metric represents the amount of revenue gained from the use of MOP per rupee spent on its application.

$$\varphi_p = \frac{[(Y_{+MOP} - Y_{-MOP}) * \rho_{crop}] - (\omega * \rho_{MOP})}{(\omega * \rho_{MOP})}$$

Equation 1

Where:

φ_p	= net benefit: cost ratio
Y_{+MOP}	= Treatment (+MOP) yield level (kg/ha)
Y_{-MOP}	= Control (-MOP) yield level (kg ha ⁻¹)
ρ_{crop}	= Crop market price (rupees kg ⁻¹)
ω	= MOP dosing rate (kg ha ⁻¹)
ρ_{MOP}	= MOP price (rupees kg ⁻¹)

4.6. Previous work

This study is a continuation of an earlier investigation with the same objectives, conducted between 2013 and 2016 across 22 field trials in the states of Andhra Pradesh, Chhattisgarh, and Madhya Pradesh. The earlier study is of particularly relevance here, as it enables side by side comparison of conclusions drawn from both studies regarding the use of muriate of potash (MOP) to improve onion yields in India.

The earlier study followed the same experimental procedures as the current work, although trial conditions differed. Soils at the trial sites were classified either as Eutric Nitisols or Thionic Fluvisols. Other soil characteristics are summarised in Figure 9 and Table 5.

Onion crops were established during the *kharif* seasons of 2015 and 2016 and the *rabi* seasons of 2013-14 and 2015-16. To ensure direct comparability with the current study, in which all trials took place during *rabi*, only the *rabi* trials from the earlier study were included in the analysis. Sowing dates ranged from 20 December to 7 February in 2013-14 (Chhattisgarh) and 30 October in 2015-16 (Madhya Pradesh).

On each farm, a pair of equally sized onion plots was laid out side by side: one control plot receiving a standard fertilizer program and one treatment plot receiving the same program plus MOP. Plot sizes within each pair were identical; however, sizes between pairs varied from 0.1 to 1.5 ha. All recommended agronomic practices were followed.

Farmyard manure was applied in only one trial at 2 t ha⁻¹. NPK fertilization was applied at rates of 25 or 125 kg N ha⁻¹ (depending on the state), 60 kg P₂O₅ ha⁻¹ and 75 or 150 kg K₂O ha⁻¹ (depending on the state). Urea and di-ammonium phosphate (DAP) served as the nitrogen and phosphorus sources, respectively. Muriate of potash (MOP; KCl) was used as the sole potassium source in the MOP treatment plots.

Table 3. Fertilizer and manure application rates for control and +K treatments in the onion field trials (previous work, Chattisgarh).

Fertilizer source	Treatment and application rate			
	kg ha ⁻¹		kg plot ⁻¹	
	Control	+ K	Control	+ K
N (from urea + DAP)	125		50	
P ₂ O ₅ (from DAP)	60		24	
K ₂ O (from MOP)	0	150	0	60

Table 4. Fertilizer and manure application rates for control and +K treatments in the onion field trials (previous work, Madhya Pradesh).

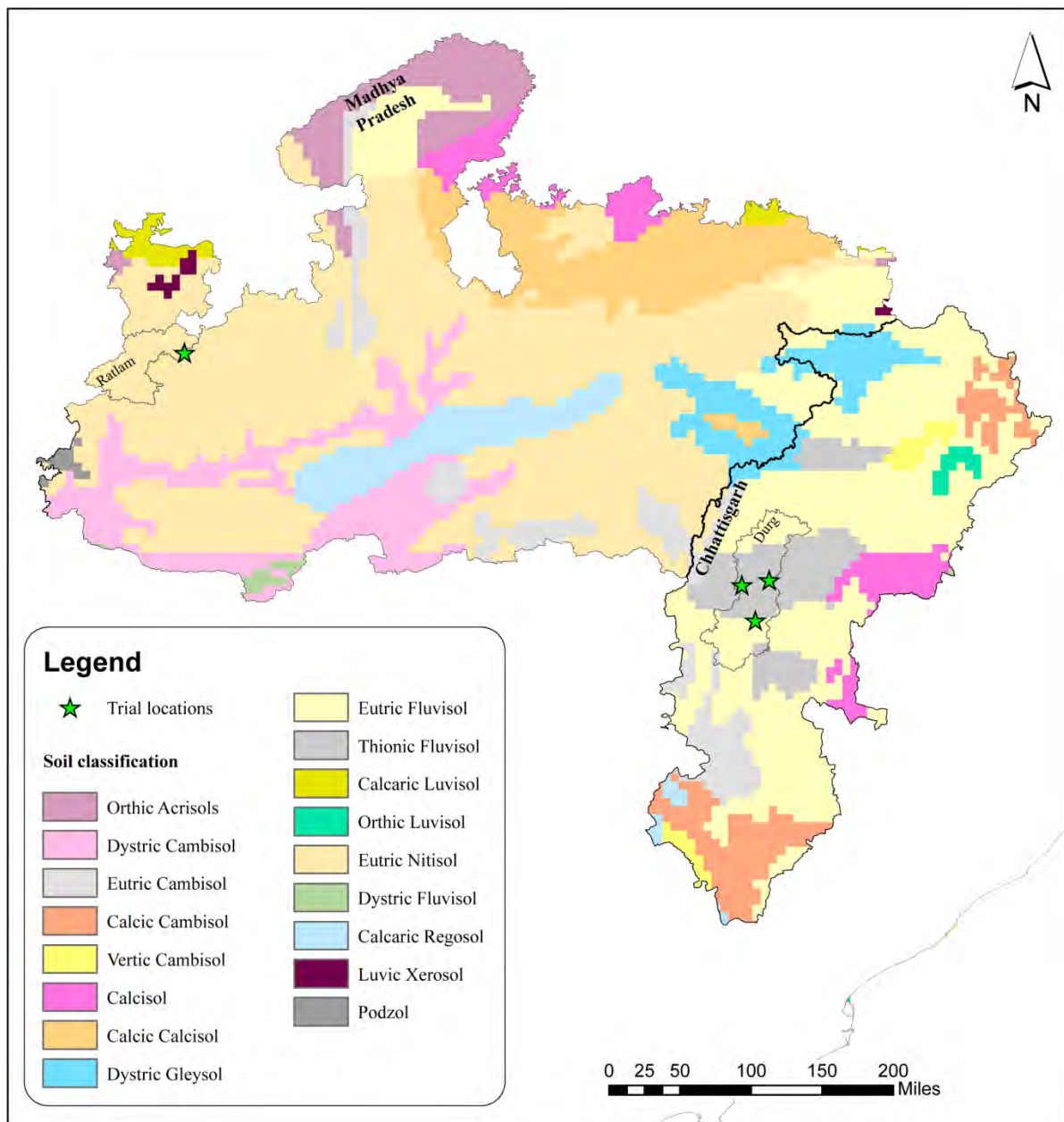
	Treatment and application rate			
	kg ha ⁻¹		kg plot ⁻¹	
Fertilizer source	Control	+ K	Control	+ K
N (from urea + DAP)	25		10	
P ₂ O ₅ (from DAP)	60		24	
K ₂ O (from MOP)	0	75	0	30
Manure	2		0.8	

Table 5. Trial soil characteristics in the earlier study

State	District	No. of trials	Soil classifications	Soil drainage class	K status	% Clay (Texture)	pH
Madhya Pradesh	Ratlam	1	Eutric Nitisol	Imperfectly drained	High	10-20% (Light)	Slightly alkaline
Chhattisgarh	Durg	5	Eutric Nitisol, Thionic fluvisol	Imperfectly drained	Medium to High	20-35% (Medium)	Normal

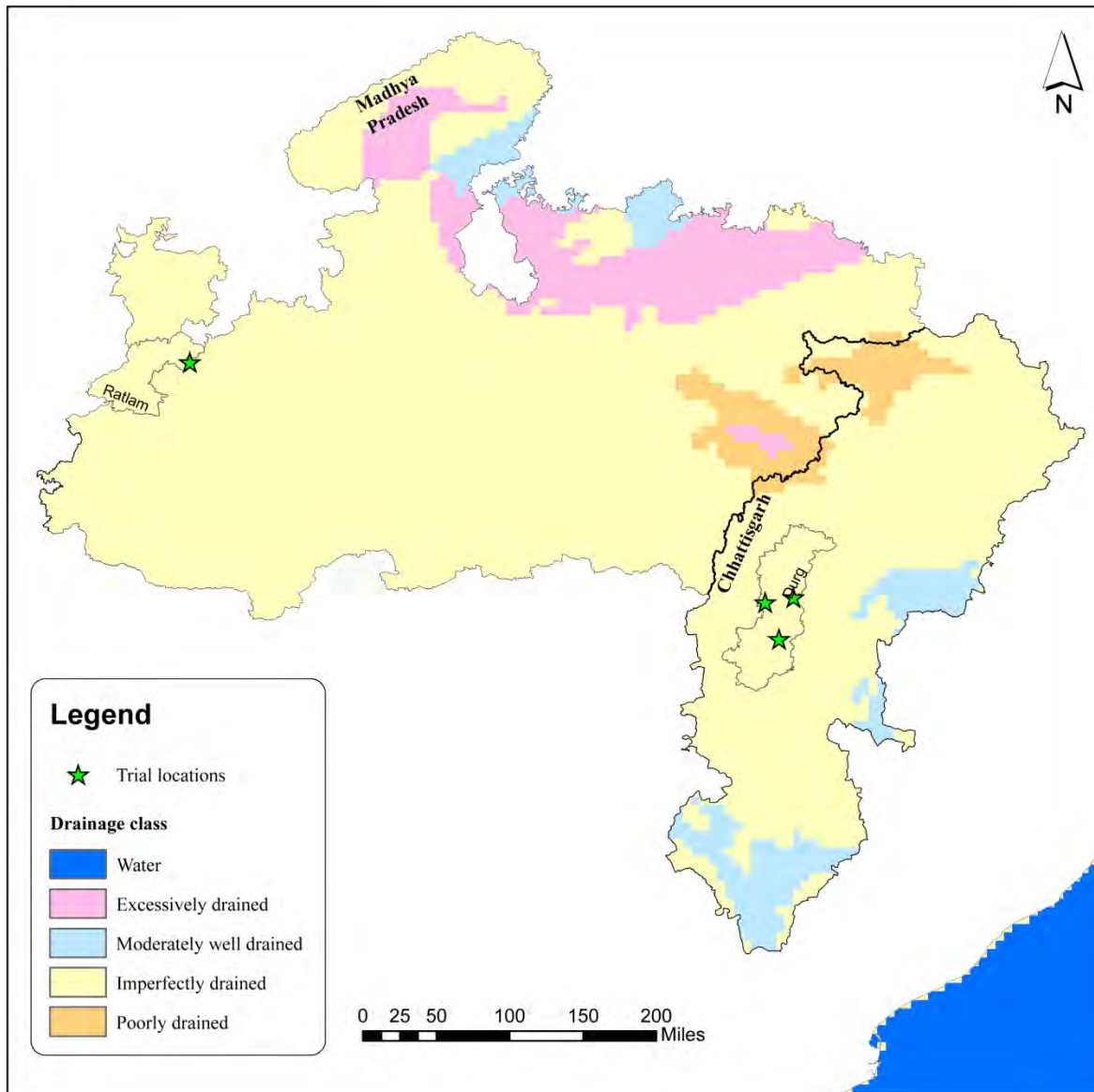
The above table details soil characteristics of the earlier study by district, including the number of trials per district, soil classifications, soil drainage class, K status, % clay (texture) and pH. These characteristics were used in investigating variations in yield levels and MOP response, in combination with climatic data. Data: (Soil and Land Use Survey of India 2025)

Figure 8. Map of the study area in earlier work showing trial locations and soil classifications (*rabi* only)



The map to the left shows the trial study areas in the earlier work (north-western Madhya Pradesh and central Chattisgarh). Trial locations are marked with green stars, with associated districts shown and labelled. The map base shows the soil classifications within the study area according to the colours in the legend. Data: (Batjes 2008, Hijman 2020).

Figure 9. Map of the study area in earlier work showing trial locations and soil drainage class (*rabi* only)



The map to the left shows the trial study areas in the earlier work (north-western Madhya Pradesh and central Chattisgarh). Trial locations are marked with green stars, with associated districts shown and labelled. The map base shows soil drainage within the study area according to the colours in the legend. Data: (Batjes 2008, Hijman 2020).

5. Results

This section describes the results of the statistical tests outlined in § 4.4.

5.1. MOP effect on yield levels

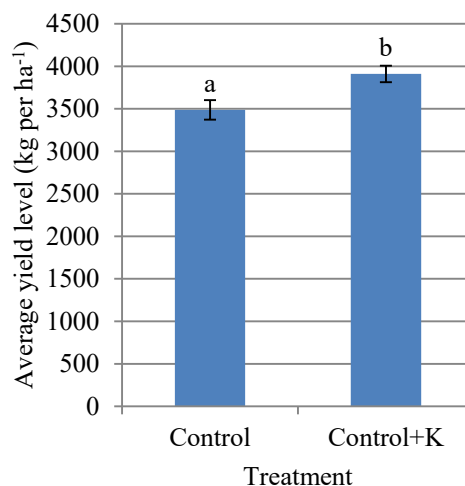
The average onion yield level in the control plots across the 35 trials was 3,488 kg ha⁻¹. In the +K plots, this increased to 3,911 kg ha⁻¹ (Figure 10).

MOP treatments had a substantial and statistically significant effect on onion yield level compared with the standard N and P treatment (t-test, $p < 0.001$). As the only source of potassium, applications of MOP brought about

clear benefits, with an average yield increase of 423 kg ha⁻¹ (Figure 11). Yield increases were observed across all 35 trials varying from 70 to 1,012 kg ha⁻¹, with a median of 304 kg ha⁻¹.

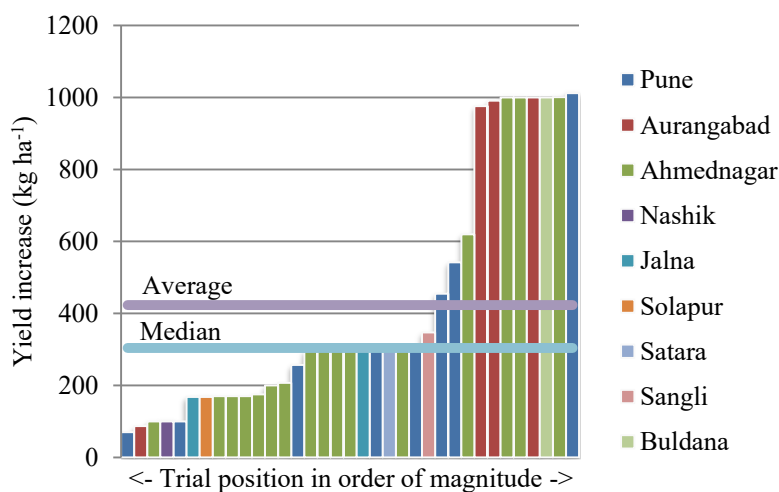
The median yield increase was 119 kg ha⁻¹ lower than the mean, indicating a positively skewed distribution of responses (Figure 12). This suggests that while all sites benefited from MOP application, the magnitude of response varied across locations. Most trials showed moderate yield gains, whereas a smaller number exhibited exceptionally high increases, likely reflecting differences in site-specific growing conditions.

Figure 10. Average onion yield (kg ha⁻¹) in control and control+K plots across 35 field trials.



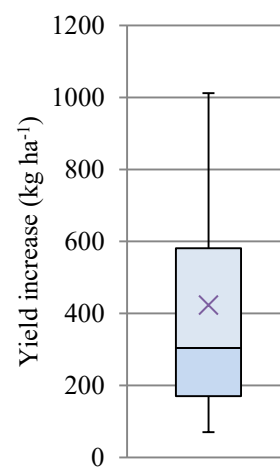
Error bars represent standard error of the mean ($n = 35$). Columns followed by different letters differ significantly ($p < 0.001$); paired two-sample t-test

Figure 11. Onion trials absolute yield increases (kg ha⁻¹) in an ordered array by district showing average (423 kg ha⁻¹) and median (304 kg ha⁻¹)



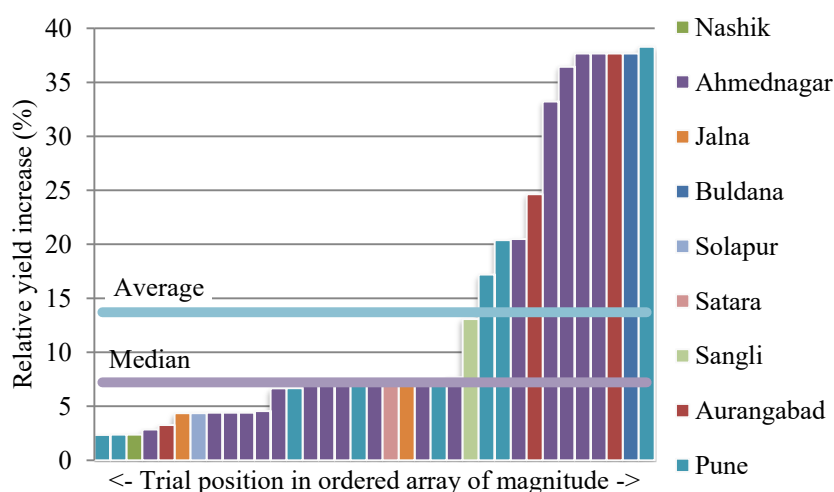
The above figure shows the distribution of absolute onion yield increases (kg ha⁻¹) across 35 field trials, arranged in order of magnitude by district. The average yield increase was 423 kg ha⁻¹ and the median 304 kg ha⁻¹.

Figure 12. Box-and-whisker plot of yield increases (kg ha⁻¹)



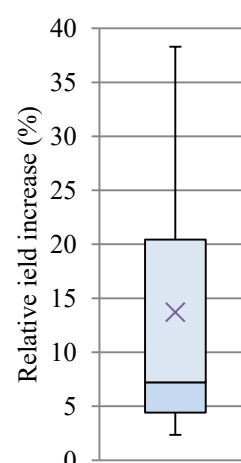
The above figure shows a box-and-whisker plot summarizing the distribution of yield increases (kg ha⁻¹) across all onion trials.

Figure 13. Onion trials relative yield increases (%) in an ordered array by district showing average (13.7%) and median (7.2%)



The above figure shows the distribution of relative onion yield increases (%) across 35 field trials, arranged in order of magnitude by district. The average yield increase was 13.7% and the median 7.2%.

Figure 14. Box-and-whisker plot of relative yield increases (%)



The above figure shows a box-and-whisker plot summarizing the distribution of relative yield increases (%) across all onion trials.

When expressed in relative terms, the distribution of yield increases was very similar to that of absolute yield gains (Figure 13 and Figure 14). This indicates that the response to MOP was broadly consistent across trials, regardless of control yield levels, i.e. variations in inherent site productivity did not affect the proportional benefits from MOP application.

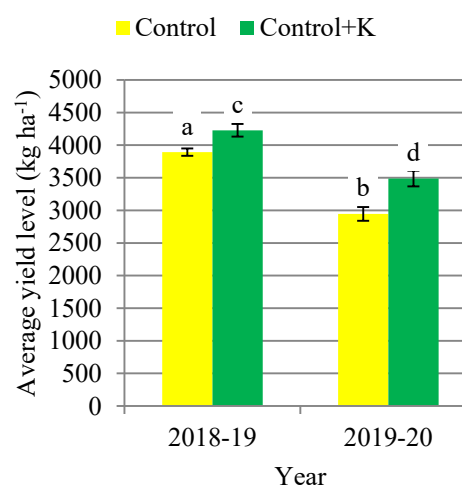
5.2. Effects of trial conditions

The following section reports the results of statistical analyses assessing how trial conditions influenced yield and MOP performance.

5.2.1. Year

Average yield levels in the control plots were 3,894 kg ha⁻¹ in 2018-19, and 2,946 kg ha⁻¹ in 2019-20, respectively (Figure 15). In the +K plots, average yields were 4,228 kg ha⁻¹ in 2018-19, and 3,488 kg ha⁻¹ in 2019-20, respectively. The differences between years for both the control and +K treatments were statistically significant ($p < 0.001$).

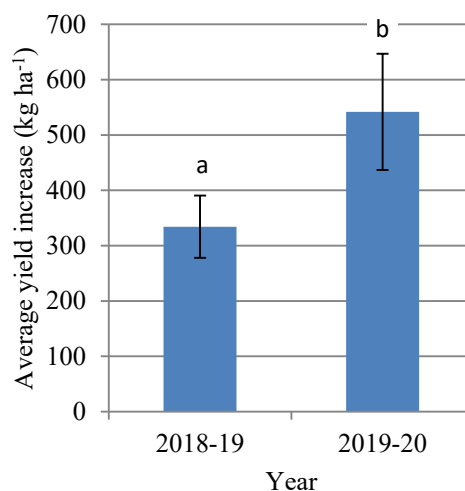
Figure 15. Average yield levels (kg ha⁻¹) during 2018–19 and 2019–20.



Error bars represent standard error of the mean ($n = 20$ and 15 , respectively). Columns followed by different letters differ significantly ($p < 0.001$); one-tailed t -tests assuming unequal variances).

Yield responses to MOP application also differed significantly between years (Figure 16). In 2018-19, the average yield increase was 334 kg ha⁻¹, while in 2019-20 it was 542 kg ha⁻¹ ($p = 0.035$). In relative terms, the difference between years was even more pronounced (Figure 17). The average relative yield increase in 2018-19 was 8.9%, compared with 20.1% in 2019-20. This difference was also statistically significant ($p = 0.004$), indicating that the proportional benefit of MOP was more than twice as large under the wetter conditions of 2019–20 compared with the drier 2018-19.

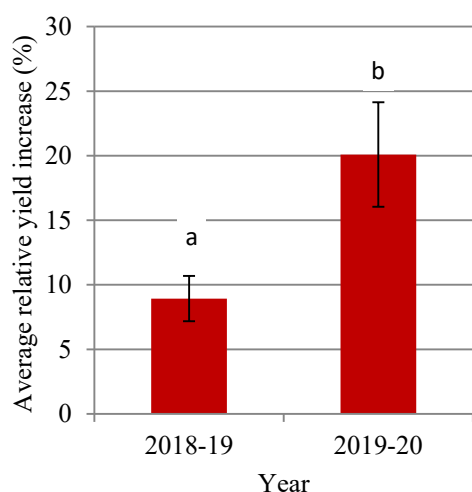
Figure 16. Average yield increase (kg ha⁻¹) in response to MOP application during 2018–19 and 2019–20.



Error bars represent standard error of the mean ($n = 20$ and 15 , respectively). Columns followed by different letters differ significantly ($p = 0.035$; one-tailed t -test assuming equal variances)

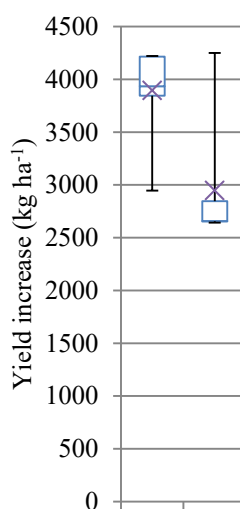
The box-and-whisker plots (Figure 18, Figure 19) show that the distributions of yield increases differed between absolute and relative metrics and between years. In 2018-19, absolute yield increases were negatively skewed, indicating that a few sites exhibited particularly low responses, whereas in 2019–20 they were positively skewed. For the relative increase data, the distribution was positively skewed in 2018–19 but approximately symmetric in 2019-20.

Figure 17. Average relative yield increases (%) during 2018–19 and 2019–20.



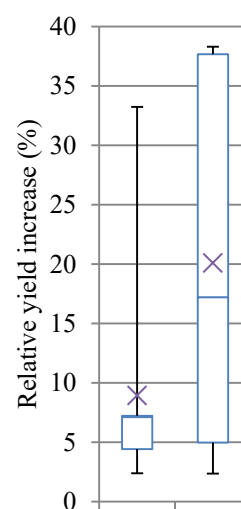
Error bars represent standard error of the mean ($n = 20$ and 15 , respectively). Columns followed by different letters differ significantly ($p = 0.004$); one-tailed t -test assuming equal variances.

Figure 18. Box-and-whisker plot of yield increases by year (kg ha⁻¹)



The above figure shows a box-and-whisker plot summarizing the distribution of yield increases (kg ha⁻¹) by year.

Figure 19. Box-and-whisker plot of relative yield increases by year (%)



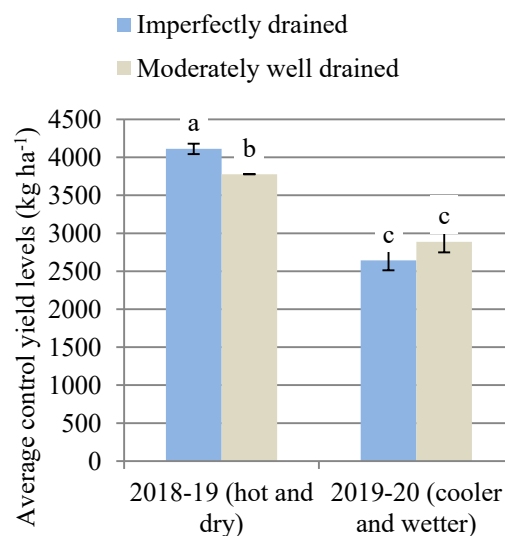
The above figure shows a box-and-whisker plot summarizing the distribution of relative yield increases (%) by year.

5.2.2. Year x drainage class

Within years, yield level varied with drainage class, consistent with a year × drainage interaction: in 2018-19, moderately well-drained sites had lower control yield levels ($p=0.019$), whereas in 2019-20 the pattern reversed (Figure 21). However, estimates for low drainage in 2019-20 are imprecise due to a very small sample size ($n = 2$).

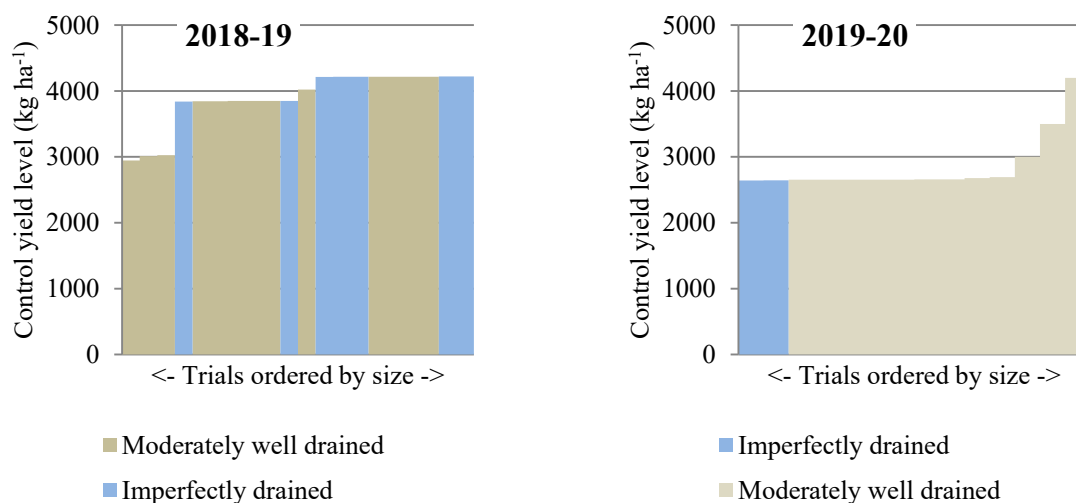
Yield increases due to MOP application also varied with year and drainage class. In 2018-19, yield responses were relatively low overall, averaging 266 kg ha⁻¹ at imperfectly drained sites and 371 kg ha⁻¹ at moderately well-drained sites. In 2019-20, when conditions were cooler and wetter, yield increases were larger in both drainage classes, averaging 734 kg ha⁻¹ and 547 kg ha⁻¹, respectively. Although the trend suggested stronger MOP responses under imperfectly drained conditions in 2019-20, the interaction between year and drainage class was not statistically significant ($p > 0.05$).

Figure 20. Average control yield levels (kg ha⁻¹) by year and drainage class.



The above figure shows average control yield levels (kg ha⁻¹) by year and drainage class. Error bars represent standard error of the mean. Columns followed by different letters differ significantly.

Figure 21. Onion control yield levels (kg ha⁻¹) by drainage class for the 2018–19 and 2019–20 seasons.

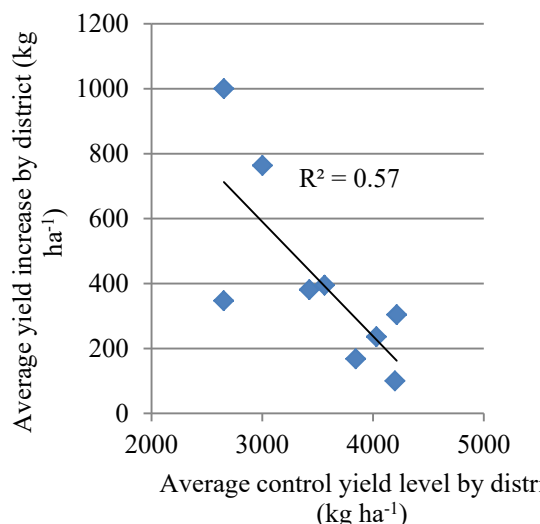


5.2.3. District

Average control yields ranged from 2,653 kg ha⁻¹ in Sangli district to 4,215 kg ha⁻¹ in Satara (Figure 22). Average yield increases following MOP application varied from 100 kg ha⁻¹ in Nashik to 1000 kg ha⁻¹ in Buldana (Figure 23). Although no statistically significant differences were observed between districts, the figures illustrate the range of values recorded across locations.

Average MOP response was inversely proportional to the average control yield level across districts ($R^2 = 0.57$; Figure 24), indicating that districts with higher control yields tended to exhibit smaller MOP responses.

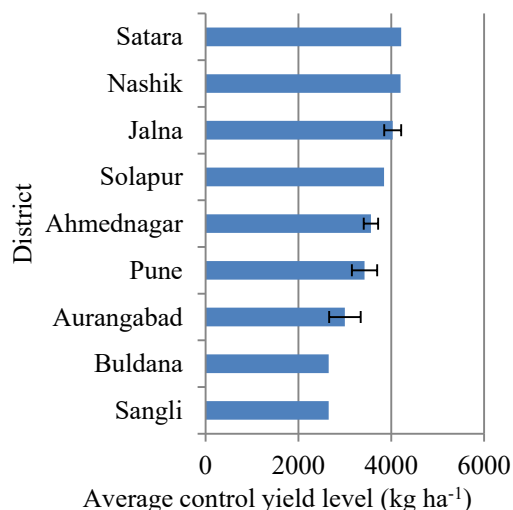
Figure 24. Relationship between average control yield level and MOP yield response across districts.



Average yield increase due to MOP application (kg ha⁻¹) is plotted against the corresponding average control yield level (kg ha⁻¹) by district. A negative correlation ($R^2 = 0.57$) indicates that MOP response declined with increasing control yield levels.

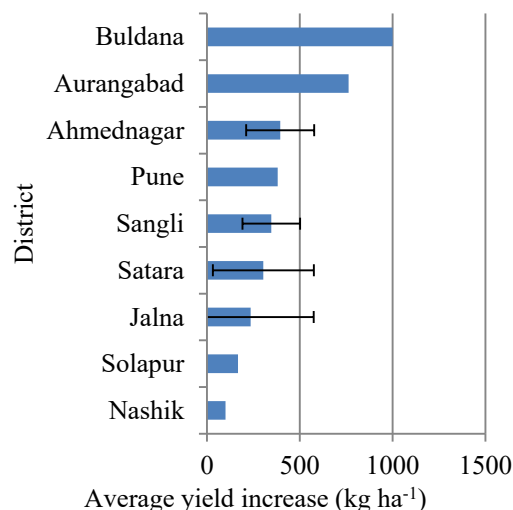
5.2.4. Profitability

Figure 22. Average onion control yield levels (kg ha⁻¹) by district



Average yield levels in the control plots (receiving N and P only) are shown for each district. Yield levels varied considerably among districts, with Satara and Nashik showing the highest averages and Sangli the lowest. Error bars represent standard error of the mean.

Figure 23. Average onion yield increases (kg ha⁻¹) by district



Average yield increases due to MOP application are shown for each district, calculated as the difference between MOP-treated and control plots. Yield responses were highest in Buldana and Aurangabad and lowest in Nashik and Solapur. Error bars represent standard error of the mean.

The profitability of MOP application was evaluated based on the average yield response and input costs across the 35 field trials (Table 6). The application of MOP resulted in an average yield increase of 423 kg ha⁻¹, corresponding to a 13.7% increase over the control plots. Assuming an average farmgate onion price of Rs 12.7 kg⁻¹, this corresponds to an average gross profit increase of Rs 5,450 ha⁻¹.

Table 6. Profitability summary table

Metric	Result	Unit
% increase:	13.7	%
Price of product:	12.7	Rs/kg
Yield increase:	423	kg/ha
Profit increase:	5,450	Rs/ha
Cost of MOP:	903	Rs/ha
Net profit:	4,457	Rs/ha
B:C ratio:	5.0	

The cost of MOP application was estimated at Rs 903 ha⁻¹, resulting in an average net profit of Rs 4,457 ha⁻¹. The resulting benefit-to-cost (B:C) ratio was 5.0. Benefit-to-cost ratios were positive in all trials except one, ranging from -0.1 to 14.3 (Figure 25). The median was 2.0 lower than the mean, indicating a positively skewed distribution of responses (Figure 26). Most trials showed moderate benefit-cost-ratios, whereas a smaller number exhibited exceptionally high increases.

Figure 25. Onion trials benefit-to-cost ratios in an ordered array showing average (5.0) and median (3.0)

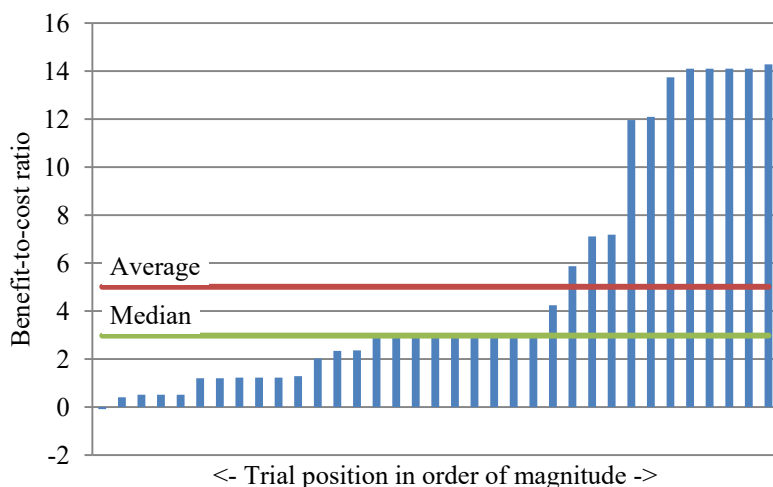
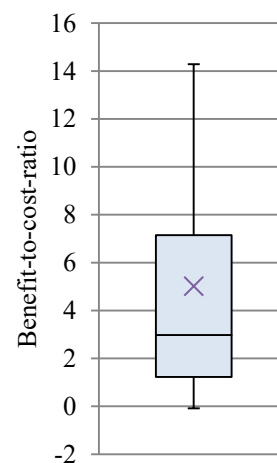


Figure 26. Box-and-whisker plot of benefit-cost-ratios



5.3. Comparison with previous work

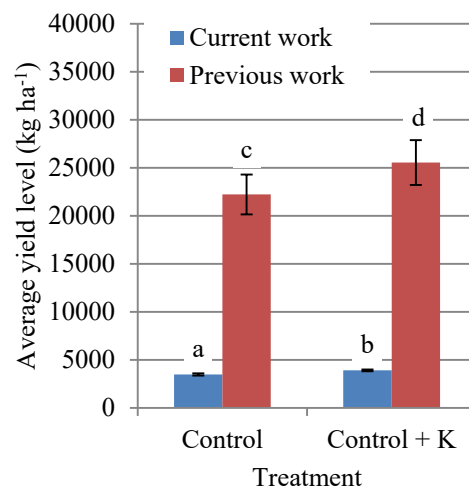
Average onion yields were substantially lower in the current trials than in the previous work (Figure 27). Mean control yields were 3,488 kg ha⁻¹ compared with 22,230 kg ha⁻¹ in the previous work, while + K yields averaged 3,911 kg ha⁻¹ compared with 25,558 kg ha⁻¹.

The absolute yield increase due to MOP application was smaller in the current trials (423 kg ha⁻¹) than in the previous work (3,329 kg ha⁻¹; Figure 28).

In relative terms, however, the two datasets showed similar proportional responses (Figure 29). The mean relative yield increase was 13.7% in the current work and 15.4% in the previous work; this difference was not statistically significant ($p > 0.05$). Thus, while yield levels and absolute gains differed substantially, the proportional response to MOP was comparable between the two study periods.

Figure 30 presents a comparison of the benefit-to-cost-ratios in the current work to those of the previous work, and the respective averages. The average benefit-to-cost ratio in the current work (5.0) was 2.0 lower than that of the previous work (7.0); however, the difference was not statistically significant.

Figure 27. Average onion yield levels (kg ha⁻¹) in the current and previous work (control and + K plots).



Different letters indicate significant differences between treatments ($p < 0.05$). Error bars represent standard error of the mean. The comparison illustrates the higher overall yield levels in the previous work relative to the current trials.

Figure 28. Comparison of average yield increase (kg ha⁻¹) between the current work and previous work.

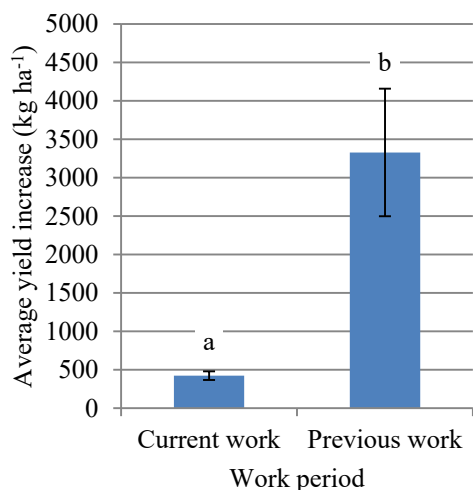


Figure 29. Comparison of relative average yield increase (%) between the current and previous work.

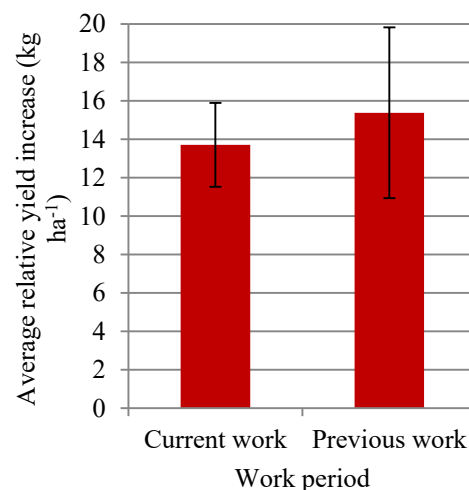
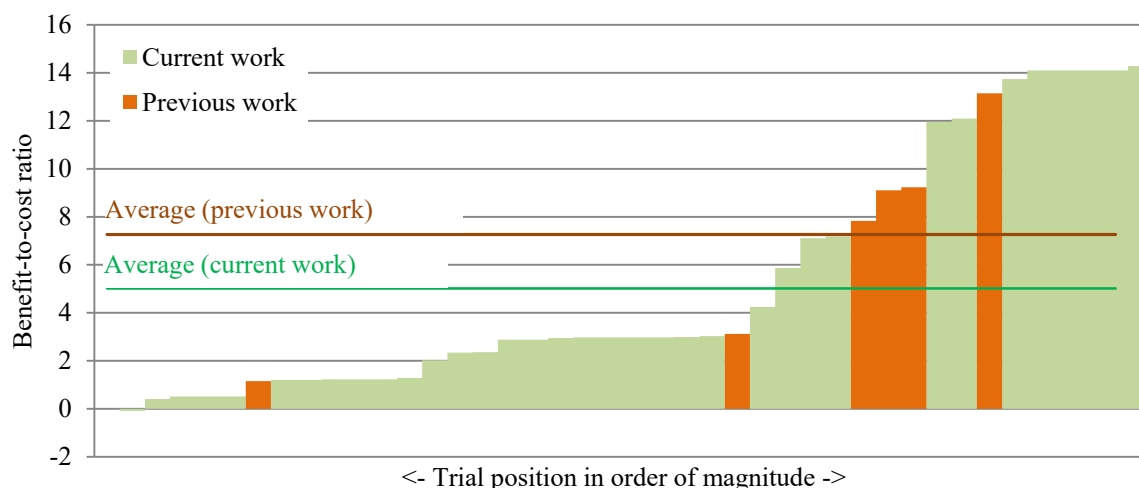


Figure 30. Comparison of benefit-to-cost-ratios in the current work to previous work, and respective averages



Each bar represents the benefit-cost ratio (B:C) of an individual trial, ordered by magnitude. Horizontal lines show the mean B:C ratio for the previous work (orange) and current work (green). Negative or low ratios indicate cases where additional K input did not offset fertilizer cost, while ratios above one represent positive economic return.

6. Discussion

6.1. MOP performance

Application of muriate of potash (MOP) significantly increased onion yields across all trial sites, confirming potassium as a key limiting nutrient under the production conditions tested. The average yield increase of 423 kg ha⁻¹ represents a meaningful agronomic gain in the context of India’s onion production systems, where profit margins are often small.

The fact that all sites recorded a positive response indicates a consistent yield benefit from MOP application. However, the distribution of responses was positively skewed, with the median yield increase approximately 25 % lower than the mean. This pattern indicates that while most sites achieved moderate yield gains, a smaller number of fields exhibited exceptionally high responses. Such variability is characteristic of field-scale experiments and likely reflects the influence of soil fertility, drainage and climate on potassium uptake and response.

6.2. Influence of seasonal conditions

Year-to-year variation was marked. Both control yields and MOP responses differed significantly between 2018-19 and 2019-20: yields were higher in the first year, whereas responses to MOP were greater in the second. In relative terms, the benefit of MOP was more than twice as large under the cooler and wetter conditions of 2019-20.

This pattern reflects how seasonal moisture conditions shaped baseline yield potential and, consequently, the yield gap available for potassium response. In the drier 2018-19 season, imperfectly drained sites retained more moisture and supported higher control yields, leaving less scope for improvement from MOP. By contrast, the cooler and wetter 2019-20 season reduced control yields overall-particularly in water-retentive soils-creating a larger yield gap and a stronger response to added potassium.

Thus, environmental factors, especially soil-water balance, acted primarily by influencing control yield levels rather than directly affecting fertilizer efficiency. This interpretation is consistent with the known sensitivity of potassium uptake and bulb development to soil physical conditions and moisture availability.

6.2.1. MOP performance by year × drainage

The year × drainage analysis highlights the central role of the soil-water regime in shaping yield potential and, consequently, the magnitude of MOP response.

- In 2018-19 (hot and dry), imperfectly drained sites retained more moisture and achieved higher control yields, leaving a smaller yield gap and correspondingly weaker MOP responses. Moderately well-drained sites, which experienced greater moisture stress, showed lower control yields but slightly higher yield increases in response to MOP.
- In 2019-20 (cooler and wetter), the pattern reversed: imperfectly drained sites recorded lower control yields yet larger yield increases, reflecting how excess moisture constrained baseline yield but created greater scope for response to added potassium. This crossover indicates that MOP response was not governed directly by drainage or water content, but rather indirectly through their influence on control yield. In drier years, sites that conserved moisture produced higher baseline yields and smaller fertilizer responses; in wetter years, those same sites became less favorable for baseline yield but more responsive to potassium addition.

Although the year × drainage interaction was not statistically significant ($p > 0.05$), the pattern consistently points to soil-water balance as a key moderator of yield and response. The results suggested that effective potassium management depends on recognizing how drainage and seasonal rainfall together shape the yield gap available for response, rather than simply enhancing potassium mobility under wetter conditions.

6.2.2. Spatial variation among districts

Differences between districts were not statistically significant, but they were still instructive. Control yields ranged from 2,653 kg ha⁻¹ in Sangli to 4,215 kg ha⁻¹ in Satara, while yield increases due to MOP varied from 100 kg ha⁻¹ in Nashik to 1,000 kg ha⁻¹ in Buldana. The inverse relationship ($R^2 = 0.57$) between control yield and MOP response suggests that the fertilizer provided the greatest benefit in lower-yielding environments-likely those with reduced baseline potassium availability or suboptimal soil moisture conditions. Conversely, where control yields were already high, intrinsic soil fertility and moisture conditions may have been sufficient to meet crop potassium demand.

6.2.3. Other factors

Other soil and management parameters (initial potassium status, organic carbon class, pH, and manure dose) showed no statistically significant effects on yield or MOP response. This suggests that potassium limitation was broadly prevalent across the study sites. However, the relatively small sample size within each category and the limited range of variation may have constrained the ability to detect weaker interactions.

6.2.4. Implications

Collectively, these findings identify the soil moisture regime-mediated through the year × drainage interaction-as the principal factor shaping yield potential and, in turn, the magnitude of MOP response. The results show that apparent fertilizer efficiency is strongly conditioned by environmental effects on baseline yield rather than by direct changes in potassium uptake under different moisture levels.

For farmers and extension services, this underscores that potassium management and water management are closely linked: practices that stabilize soil moisture also stabilize yield potential and reduce the variability of potassium response. Accordingly, the timing, rate, and placement of MOP should be adapted to local drainage conditions and anticipated rainfall patterns, rather than solely to nutrient demand, to optimize both yield and return on investment.

6.3. Differences between studies

Average onion yields and absolute yield increases observed in the current trials were substantially lower than those reported in the earlier study. This outcome was expected, as the two study periods involved distinct production environments, and the magnitude of yield

differences is consistent with those typically observed across India (Government of India 2024).

Despite these large differences in absolute yield levels and magnitude of response, the relative yield increases due to MOP application were statistically similar between the two datasets (13.7 % vs 15.4 %, $p > 0.05$). This indicates that the proportional benefit of potassium fertilization was robust across contrasting production contexts, even where absolute yields differed substantially.

The similarity in relative response suggests that onion crops exhibit a broadly consistent physiological response to potassium supplementation once other nutrients are non-limiting, and that yield potential scales with baseline productivity rather than altering the relative efficiency of potassium use. In practical terms, this suggests that MOP remains effective across diverse onion-growing environments.

6.4. Profitability

The resulting benefit-to-cost (B:C) ratio of 5.0 indicated that for every rupee invested in MOP fertilizer, farmers could expect a fivefold return. This demonstrates that MOP application was economically advantageous under the conditions tested. However, the range of benefit-to-cost ratios was large (14.4), suggesting that although all but one site benefited from MOP application, the magnitude of response varied across locations. Most trials showed moderate benefit-cost-ratios, whereas a smaller number achieved exceptionally high values. This reflects the range of yield increases across the trials.

The average benefit-cost ratio in the previous work (7.0) was two units higher than that of the current work, though the difference was not statistically significant. The higher profitability in the previous work arose from the higher average MOP performance in absolute terms (Figure 28), which was almost an order of magnitude greater. Though the performance of MOP in the previous work was considerably higher than in the current work, this did not translate into a proportional difference in profitability. This was because MOP application rates in the previous work were higher (75-150 kg ha⁻¹) than in the current work (50 kg ha⁻¹), while the farmgate price of onions was roughly half (Rs 6 kg⁻¹ compared with Rs 12–14 kg⁻¹). Consequently, the higher yield responses in the earlier trials were offset by lower product value and higher input cost, resulting in statistically similar average benefit-cost ratios between the two study periods.

7. Conclusions and recommendations

Across 35 *rabi*-season field trials in Maharashtra, supplementing standard N and P fertilization with muriate of potash (MOP) consistently increased onion yield. The mean gain was 423 kg ha⁻¹ (median 304 kg ha⁻¹), equivalent to a 13.7% improvement over controls. Responses were positive at all 35 sites, confirming potassium as a limiting factor under the production conditions tested.

Environmental conditions dominated the pattern of responses. Statistical tests identified year (weather) as the strongest driver of both control yield and MOP response, followed by drainage class. The cooler, wetter 2019-20 season produced larger absolute and relative responses (542 kg ha⁻¹; 20.1%) than the warmer, drier 2018-19 season (334 kg ha⁻¹; 8.9%). A year × drainage interaction was apparent, indicating that soil moisture regime primarily influenced control yield levels, which in turn determined the apparent magnitude of MOP response. In dry years, imperfectly drained soils retained more moisture and achieved higher control yields but smaller yield gains from added K. In wetter years, those same sites exhibited lower control yields yet greater yield increases, reflecting the inverse relationship between baseline yield and yield gap closure through potassium fertilization.

Spatially, district had little to no statistical effect once environmental and soil variables were accounted for, implying that geographic location was less impactful than field-specific conditions. Importantly, MOP response was inversely related to baseline control yield across districts ($R^2=0.57$): lower-yielding environments showed greater benefits from added potassium, consistent with diminishing marginal returns where inherent potassium supply or yield potential are higher.

From an economic perspective, MOP application was profitable in all but one of the trials. Using contemporary prices and the observed yield responses, the mean benefit: cost ratio was 5.0, indicating a fivefold return per rupee invested. The positively skewed distribution indicates that most sites reported moderate gains and a few very high gains.

When compared with earlier *rabi* trials (2013-2016), absolute yields and yield increases were much lower in the current work, reflecting differences in production context, management intensity and yield potential. However, relative (%) yield increases, and profitability were statistically similar, indicating that the proportional efficiency of potassium fertilization remains robust across diverse onion-growing systems.

7.1. Implications for practice

- Prioritize site-specific potassium management focused on fields with lower baseline yields or indicators of potassium limitation.
- Account for seasonal weather and drainage when planning potassium rates and timing, as these factors determine yield potential and the size of the yield gap that added potassium can close.
- Maintain balanced nitrogen and phosphorus programs while using muriate of potash (MOP) strategically to address potassium-related limitations and stabilize profitability across variable seasons.

Limitations include unbalanced replication within some drainage classes (notably low-drainage sites in 2019–20) and the inherent variability of on-farm trials. These do not conflict with the central findings but rather suggest caution when extrapolating the interpretations.

8. Recommendations for further work

- Expand replication across drainage classes and seasons to refine estimates of the year \times drainage interaction.
- Test rate-response relationships for muriate of potash (MOP) under contrasting moisture regimes to quantify how yield gap closure varies with baseline yield.
- Integrate soil and tissue potassium diagnostics to strengthen the targeting of fields likely to show the largest economic response.

Appendix: Example soil nutrient status maps (Indian Government)

Figure 31. Available potassium Ahmednagar district, Maharashtra

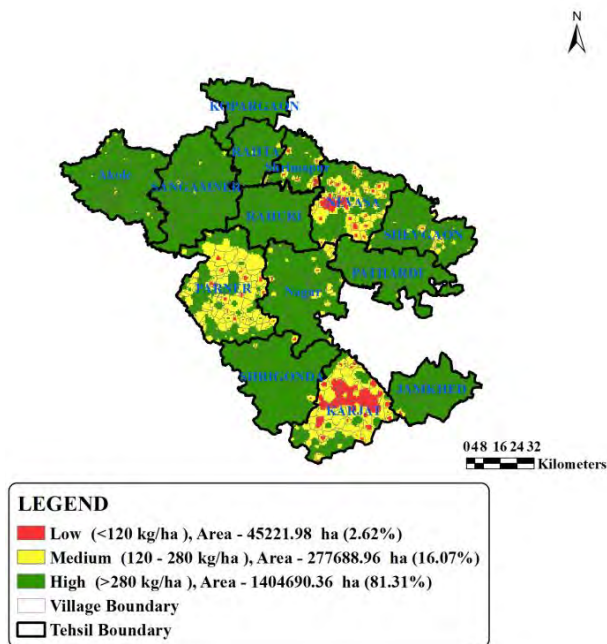


Figure 32. Available potassium Pune district, Maharashtra

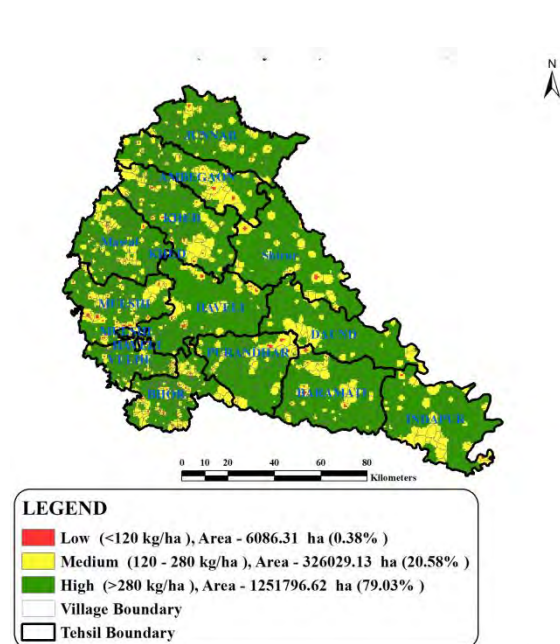


Figure 33. Percent organic carbon (SOC) Aurangabad district, Maharashtra

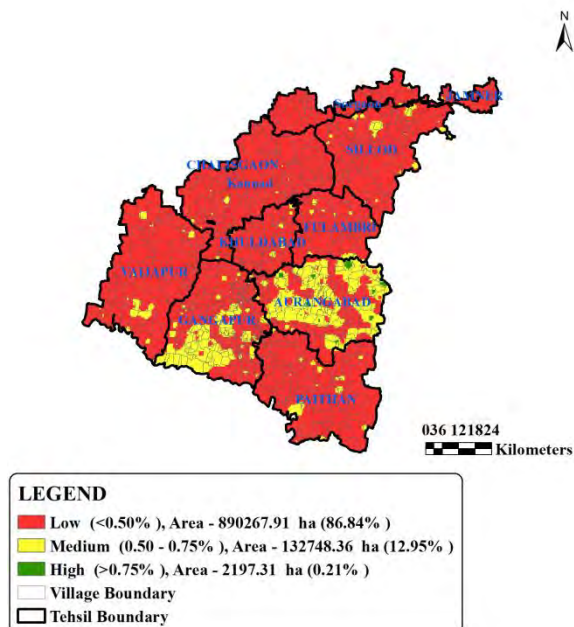
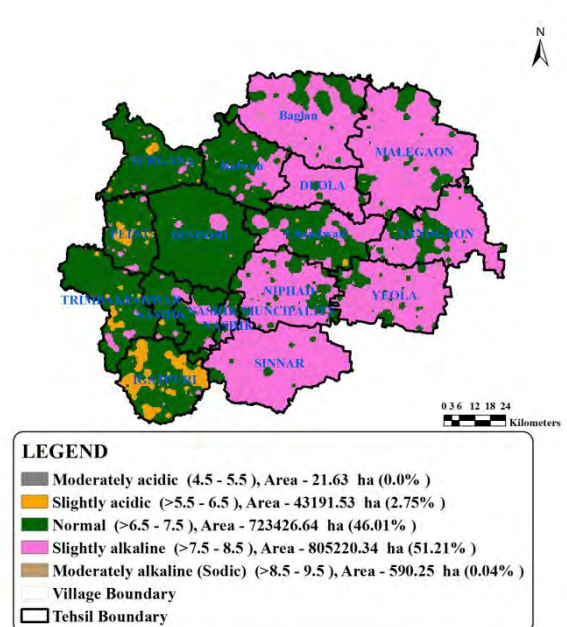


Figure 34. Soil pH Nashik district, Maharashtra



Maps showing district-level distributions of key soil fertility parameters in Maharashtra, including available potassium (Ahmednagar and Pune), percent organic carbon (Aurangabad), and soil pH (Nashik). Classes correspond to Soil Health Card (SHC) Cycle-II thresholds. Source: (Soil and Land Use Survey of India 2025)

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