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Risk-return trade-offs in diversified cropping systems under conservation agriculture: Evidence from a 14-year long-term field experiment in north-western India

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ABSTRACT

Conservation agriculture practices are promoted to increase productivity, profitability, and sustainability across diverse cropping systems. Many studies have used these goals in decision support frameworks to identify the most effective treatment among those examined. While this approach is valuable, it lacks actionable guidance for farmers regarding maximizing return, while minimizing risk. It does not provide specific recommendations on how to allocate land across various cropping systems and tillage practices to achieve such objectives. This would require another long-term experiment exploring various combinations of treatments. To address this challenge, we propose the application of modern portfolio theory, specifically leveraging mean-variance and conditional value at risk optimization models. Using these models has enabled us to identify the optimal cropping system combinations with different tillage practices that maximized yield and net returns with minimal associated risk. The proposed approach allows for recommendations involving combinations of treatments that may not have been previously tested in a geography. In a 14-year long-term conservation agriculture study involving twelve combination of tillage and cropping systems, we showed how different combination of treatments differ in risk-return profile using mean-variance and conditional value-at-risk models that trace out a frontier of options—combinations of treatments that give highest returns at minimal risk. For example, we find that across risk neutral (most profitable) and most risk averse (lowest risk) farmers, the optimal treatments on the frontier encompass of maize-mustard-mungbean (MMuMb) under zero tillage and maize-wheat-mungbean (MWMb) under bed planting (which offer high returns and associated risk), maize-maize-*Sesbania* (MMS) under zero tillage (providing a balance of moderate returns and risk), and MMS under conventional tillage (yielding lower returns and risk). Additionally, risk-averse farmers stand to gain by diversifying their land allocation. For instance, they could allocate 54 % of their land to MMuMb under zero tillage and 46 % to MWMb under bed planting to target net returns of INR 1,32,000, with downside risk of INR 56,000, otherwise they can allocate 44 % and 56 % of their land to MMS under zero tillage and MWMb under bed planting, respectively, with a targeted net return of INR 1,22,000 and downside risk of INR 43,540. This highlights the nuanced trade-off between risk and return in maize based diversified cropping systems under different tillage practices. Leveraging mean-variance and conditional value at risk optimization models in the analysis of long-term experiments can yield novel treatment combinations that hold promise and can be recommended to farmers for implementation.

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1. Introduction

The rice-wheat cropping system, spread over 10.3 million ha in Indo-Gangetic Plains (IGP) of India and South Asia is the backbone of regional food and livelihood security (Dhanda et al., 2022). The green revolution succeeded in harnessing productivity gain in Northwestern-IGP regions with higher irrigation, inorganic fertilizer use, improved varieties, and mechanization. However, growing evidence has postulated the negative effects of these intensive and yield-maximizing production practices on soil degradation, groundwater depletion and productivity stagnation (Bhatt et al., 2021). This has prompted proposals for alternative cropping systems especially diverse maize-based cropping systems and conservation agriculture, which has potential for resource conservation (Dutta et al., 2023; Parihar et al., 2016). Conservation agriculture (CA) has three key resource conservation practices of minimum soil disturbance, permanent soil cover, and crop diversification. The combined effect of these practices promises higher productivity, profitability, and environmental benefits in medium to long-run-in different geographies and cropping systems (Kumara et al., 2020; Jat et al., 2020a). In the Northwestern IGP, for instance, transitioning to a conservation agriculture system with maize as the focal crop, complemented by the inclusion of mungbean, i.e., the maize-wheat-mungbean rotation in lieu of the traditional rice-wheat rotation, not only improves the profitability but also mitigates global warming potential (Jat et al., 2020).

Over the past decades, several studies have documented both medium- and long-term yield and economic benefits of maize-based diversified systems under CA (Kumara et al., 2020; Parihar et al., 2016; Parihar et al., 2018a; Parihar et al., 2018b; Parihar et al., 2018c). With superior crop health, early canopy development, and sustenance of partial green canopy till maturity (Nayak et al., 2022), the CA practices are expected to be resilient to climatic fluctuations and pest pressures (Umar, 2021). Thus, across years CA practices not only ensure heightened productivity but also serve as a strategic buffer against potential production risks. There are however many studies conducted in farmer fields that provided mixed evidence of the effectiveness of CA practices (e.g., Giller et al., 2009, 2015). The extent of productivity gain in CA is highly variable, which depends on climate, soil, and how the three practices of CA are implemented (Pittelkow et al., 2015).

Even though long-term experiments can identify the most profitable and productive cropping systems, conventional statistical analyses often fall short of offering guidance on whether it could be advantageous for farmers to allocate their land to multiple different cropping systems to optimize returns and minimize risk. Leveraging the principles of modern portfolio theory to analyze the long-term experiments holds promise in elucidating the nuanced interplay between production threats and returns across varying climate years. The existence of long-term experiments on multiple cropping systems presents a unique opportunity to delve into these temporal risk-return trade-offs, ultimately yielding robust recommendations for maximizing return with various level of production risks.

There are two distinct threads of literature addressing the risk-return trade-offs within maize based diversified cropping systems under different tillage practices, but their application in long-term studies is relatively limited. The first strand delves into how crop diversification serves as a strategy to mitigate risks (Burbano-Figueroa et al., 2022; Paut et al., 2020, 2019; Bodin et al., 2016; Mitter et al., 2015). These studies use the mean-variance (E-V) optimization model based on modern portfolio theory (MPT) initially proposed by Markowitz (1952). However, it's worth noting that the mean-variance approach has its limitations, as variance may not always serve as an accurate risk measure. It is most effective when yields follow a normal distribution and assumes that farmers are equally concerned about both upward and downward risks. Sukcharoen and Leatham (2016) have argued that intertemporal yield distributions are mostly nonnormal and farmers tend to be more focused on mitigating downside risks. They suggested employing the conditional value at risk measure, also known as mean-expected shortfall, which specifically addresses the likelihood of a yield loss surpassing a certain predefined percentile of the yield distribution. In this study, we adopted both methods to ensure the robustness of the proposed land allocations. The second strand of literature assesses the risk associated with economic returns in the context of conservation agriculture (Ngwira et al., 2013). For instance, Ngwira et al. (2013) determined that risk-averse farmers in Malawi would find conservation agriculture preferable, but those in higher elevations might require substantial incentives to adopt these technologies.

We have applied two computational risk models, specifically a mean-variance quadratic optimization model and a mean-conditional value at risk model. These models are used to identify the optimal CA-diversified cropping system combinations from a 14-year long-term experiment conducted at the ICAR-Indian Agricultural Research Institute (IARI), New Delhi research farm. We hypothesized that diverse cropping systems exhibit varying risk and return profiles in different production years. To optimize profitability while mitigating risk, we turn to the principles of modern portfolio theory (MPT), specifically employing mean-variance (E-V) optimization, as well as mean-expected shortfall measures, to allocate weights to the different cropping systems, so that farmers based on their expected return and risk bearing ability can choose different combination of cropping systems.

2. Materials and methods

2.1. Trial location and design

A long-term field experiment was initiated in 2008 and has been ongoing until 2023 at the research farm of the Indian Council of Agricultural Research (ICAR)-Indian Agricultural Research Institute (IARI), New Delhi (28° 40' N, 77° 12' E, and 228.6 m elevation). The soil at the site is characterized as sandy loam with a pH of 7.8, electrical conductivity (EC) of 0.32 dS m^{-1}, and $KMnO_4$ oxidizable N of 158.4 kg ha^{-1}. The location experiences a semi-arid climate, receiving an average annual rainfall of 650 mm, with 70–80 % occurring during the *kharif*/rainy season. The experiment encompasses three distinct tillage and crop establishment methods: (I) Conservation agriculture (CA)-based Bed Planting (PB), (II) CA-based Zero Tillage Flat (ZT), and (III) Conventional Tillage (CT), all under four diversified cropping systems, namely MWMb, *kharif*/rainy season maize (*Zea mays* L.)-winter/rabi season wheat (*Triticum aestivum*)-summer season mungbean (*Vigna radiata* L. Wilczek); MCS, *kharif*/rainy season maize – winter/rabi season chickpea (*Cicer arietinum* L.)- summer season *Sesbaina* (*Sesbania acculata*); MMuMb, *kharif*/rainy season maize- winter/rabi season mustard (*Brassica juncea*)- summer season mungbean; MMS, *kharif*/rainy season maize- winter/rabi season maize- summer season *Sesbania*. The experiment was conducted using a split plot design, with three tillage practices in the main plots and four diversified cropping systems in the sub-plots, replicated three times.

2.2. Tillage and crop establishment methods, crop cultivar, and fertilizer use

For zero tillage (ZT) plots, a ZT planter with inverted 'T' tynes was used for planting with surface retained residue. Bed planting was carried out on a 37 cm wide flat top beds with a furrow depth of 15 cm and mid-furrow to mid-furrow distance of 67 cm. Beds were reshaped annually. The quality protein maize variety HQPM1 was sown until the *kharif* season of 2016, after which the PMH1 variety, with similar duration and yield potential, was adopted. In the *rabi*/winter season, the mustard cultivar Pusa Bold was initially used for three years and was subsequently replaced by NRCDR-2 until 2017. From then on, PM-30 was sown, with a seed rate of 5 kg ha^{-1}. The chickpea cultivar P 362 was used for the first three years, succeeded by the Pusa 547 cultivar, sown in the last week of October at a seed rate of 80 kg ha^{-1}. The wheat cultivar PBW 343 was replaced by HD 2967 after the initial five years and was sown in the second or 1st fortnight of November with a seed rate of 100 kg ha^{-1}. During the summer season, Pusa Vishal mungbean cultivar was planted for the first nine years, followed by the Samrat cultivar with a seed rate of 25 kg ha^{-1} in MWMb and MMuMb systems. In MCS and MMS systems, a local cultivar of *Sesbania* was grown as green manure. *Kharif*/rainy season maize was sown in the first fortnight of July each year. Rainy season maize received a nitrogen dose of 150 kg ha^{-1}, 60 kg P_2O_5, and 40 kg K_2O ha^{-1}, while slightly higher doses were applied for *rabi*/winter maize, *i.e.*, 180 kg N, 80 kg P_2O_5, and 60 kg K_2O ha^{-1}. For winter wheat, a fertilizer dose of 120 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} was applied until 2013–14, and subsequently increased to 150 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1}. Mustard received a basal dose of 90 kg N, 40 kg P_2O_5, and 30 kg K_2O ha^{-1}. Chickpea was fertilized with 30 kg N, 40 kg P_2O_5, and 40 kg K_2O ha^{-1} at seeding. Irrigation was applied to ensure stress-free growth, with CA plots receiving 45–50 mm and CT plots receiving 60–65 mm of irrigation water, during a normal year. For additional details on agronomic practices such as weeding, residue management, as well as soil and weather properties, Parihar et al. (2016) can be referred.

2.3. Yield and economic observations

As part of long-term experiment, comprehensive soil property and crop biometric observations were collected at regular intervals. Crop productivity and economic data of particular interest for the risk-return tradeoff analysis were obtained as follows. At maturity, crops were harvested at specific heights: 15 cm above ground for chickpea, 20 cm for wheat, 35 cm for mustard, and 40 cm for maize. Grain/seed and straw/stalk yields of wheat, mustard, and chickpea were estimated from randomly selected 2.0×4.0 m^2 (8.0 m^2) harvested areas from each plot using a plot thresher (with straw/stalk amount reduced by 30 % left on the ground). Maize cobs and stover were harvested from a 10.72 m^2 area (central 4 rows constituting 4 m length with row spacing of 0.67 m) and threshed using a maize plot sheller to estimate grain yield (with stover amount reduced by 30 % left on the ground). Grain/seed moisture content was determined using a grain moisture meter and adjusted to ~14 %, 12 %, 12 %, 12 %, and 10 % moisture content for maize, wheat, chickpea, mungbean, and mustard, respectively. Economic analysis considered only variable production costs, including human labor, machinery usage (tractor, plough, planter, etc.), input costs (seed, fertilizer, herbicide and pesticide), irrigation, harvesting, threshing, loading/unloading, and transportation to the market. Land value and other fixed cost like machinery use was not considered in the analysis. The gross return was calculated by multiplying the total productivity with minimum support price fixed by government of India. Net return or profitability (NR) was calculated by subtracting total variable production costs from gross returns. The productivity data of *kharif* maize was used to build target yield and profit/net return frontier for kharif season, whereas the *rabi*/winter season crop return and system return derived from the respective yield were used to derive the profit frontier for *rabi*/winter season and cropping system, respectively. We analyzed each season separately and as well as at cropping system level too, because for some farm only one season can have more priority over other. The soil properties of respective plots can also be obtained from Parihar et al. (2016).

2.4. Frontier for return maximization and risk minimization

2.4.1. Mean-variance and mean-conditional value at risk (CVaR) optimization models

We assume a whole farm setup in which the farmer has the objective of maximizing whole farm profits at minimum risk by planting an optimal combination of cropping system and tillage practices. Thus, the total portfolio consists of different CA-patterns, each represented by a specific share. This farmer optimization is achieved using a mean-variance quadratic optimization model. Consider a farmer who selects an optimal mix (shares=α) of CA-crop pattern by minimizing the risk (portfolio variance) subject to constraints of target yield (return), and each combination of CA-pattern should have positive share and sum being 1 (sum of shares and non-negativity of shares) (Sukcharoen and Leatham, 2016). By carefully selecting the optimal crop mix that minimizes risk while adhering to the yield constraint and ensuring positive shares, the farmer can achieve a balanced and efficient portfolio that maximizes productivity and stability. The details of modelling approach are explained below:

$$\min_{\alpha_1,\ldots,\alpha_n} \sum_i \sum_j \alpha_i \alpha_j \sigma_{ij} \tag{1}$$

Subject to:

$$\sum_i \alpha_i y_i = \lambda \tag{2}$$

$$\sum_i \alpha_i = 1 \tag{3}$$

$$\alpha_i \geq 0 \text{ for all } i \tag{4}$$

where σ_{ij} is covariance of yields (or net returns) for the treatments i and j, y_i is yield mean of treatment i, α: share of land that should be allocated to the treatment and λ is the target yield. The constraint equation $\sum_i \alpha_i = 1$ restricts the shares of farmers or land allocated to each tillage and cropping system combination to add up to 1. The final constraint is the non-negativity constraint (i.e., shares can only be positive). The results from the quadratic optimization model are optimal shares of each cropping system/crop-tillage combination. The mean-variance approach is however criticized for assuming that farmers are equally concerned with upside risk as downside risk, that the returns distribution is normally distributed, and that farmers have quadratic utility functions. The criticisms on the latter assumptions are however contested and disputed in Markowitz (2014). Nonetheless, to address these potential challenges, we also use a mean-conditional value at risk (CVaR) which according to Sukcharoen and Leatham (2016) is appropriate for non-normal data. Using the notation above, we solve the mean-conditional value at risk (CVaR) model (Sukcharoen and Leatham, 2016),

$$\min_{\alpha_1,\ldots,\alpha_n} \mathrm{ES}_\beta = -\mathrm{E}\left[\sum_i \alpha_i y_i \middle| \sum_i \alpha_i y_i \leq q\right] \tag{5}$$

Subject to:

$$\sum_i \alpha_i y_i = \lambda \tag{6}$$

$$\sum_i \alpha_i = 1 \tag{7}$$

$$\alpha_i \geq 0 \text{ for all } i \tag{8}$$

where ES_β is the expected short fall, q is the βth percentile of the yield distribution ($\Pr(Y \leq q) = \beta$) assumed to be 10 % in this paper following Sukcharoen and Leatham (2016). We also conducted sensitivity analyses of this percentile by assuming 20 %, 5 % and 1 % and the result did not differ significantly (Supplementary figure B1, B2, and B3). According to Sukcharoen and Leatham (2016), ES is the expected portfolio yield loss; it represents the negative of the mean of portfolio yields that are lower than the βth percentile. The portfolio optimization models were implemented using a quadratic programming solver in an R package called fPortfolio (Wurtz et al., 2009). R codes for reproducing the analyses are in supplementary materials.

We followed a hypothetical mean-variance frontier as shown in Fig. 1. The frontier represents the set of all risk-returns options for a risk neutral (at maximum profit, e.g., T1) and most risk averse (at minimum risk, e.g., T4).

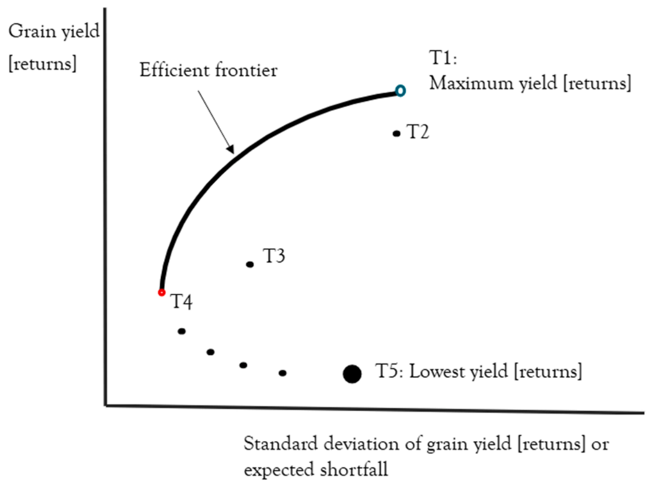

Fig. 1. A hypothetical mean-variance frontier showing yield variation, source [adapted from Wuertz et al., 2009]. The T1 has maximum yield as well as maximum risk, whereas the T4 has minimum return as well as minimum risk. **Note:** For the above mean-CVaR frontier, the x-axis is the CVaR risk measure. The solid line is the frontier representing maximum returns for each of the risk points from T1 (maximum returns point) to T4 (minimum returns point). The dotted lines represent the minimum variance locus but not on the frontier because there is a least risk portfolio with higher returns, i.e., T4.

3. Results

3.1. *Kharif* maize productivity and profitability evaluation

The maize productivity varied significantly across tillage and cropping system combinations (Fig. 2a). The largest average maize yields of ~5.6 t ha^{-1} were observed under ZT-MCS and PB-MCS. The least average maize yields were obtained under CT-MMS (~4.6 t ha^{-1}). Within the same cropping systems, the CA-based ZT treatments demonstrated notably superior yields compared to CT, although not significantly different from PB treatments. On average, the adoption of CA led to a 13 % increase in maize yield under CA-based ZT and an 11 % increase under PB in the MWMb system as compared to CT. Among the cropping systems, PB-MMuMb and ZT-MMuMb responded most to CA, showcasing yield gains of approximately 16 % (equivalent to 0.75 t ha^{-1}) and 15 % (equivalent to 0.70 t ha^{-1}), respectively. The choice of cropping system also played a vital role; irrespective of tillage practices, the yield under MMS system was least while the MCS system produced the highest yields. In tandem with the enhanced productivity, Fig. 2b illustrates that profitability was notably higher under MWMb and MCS systems, particularly when grown under CA-based PB and ZT practices. On the other hand, the CT-MMS and CT-MMuMb system demonstrated the least profitability.

The mean-variance frontier, focusing on *kharif* maize net returns, reveals that ZT-MCS was the sole cropping system offering both maximum return and risk neutrality (Fig. 3 and Fig. 4). In contrast, the scenario with the least risk, catering to the most risk-averse farmer, features CT-MMS only, but the yield and net return of the system was least. In these extreme cases, a farmer would allocate the entire plot area to these respective treatments. For moderately risk-averse farmers, there exist several potential optimal combinations of treatments. For instance, a hypothetical farmer with a moderate risk tolerance and a targeted maize yield of 5.05 t ha^{-1}, the frontier suggests allocating 47 % of the area to the CT-MMS system, 31 % to ZT-MCS, and 21 % to ZT-MMuMb system. In terms of the net return frontier, a moderately risk-averse farmer aiming for maize net returns of INR 52,500 should optimally allocate 51 % to CT-MMS, 40 % to ZT-MCS, 7 % to ZT-MMuMb, and 2 % to ZT-MWMb. However, a risk-tolerant farmer aiming for maize productivity exceeding 5.5 t ha^{-1} could allocate either 100 % of their land to ZT-MCS or divide it between ZT-MCS and ZT-MMuMb in a 4:1 ratio (as detailed in Fig. 3). The net return frontier also indicates a similar allocation of land for a farmer aiming to maximize returns (Fig. 4). The practical realities of implementing these portfolios need to be considered especially in cases where a very small proportion of the land is allocated to a particular system.

The optimal weights for various maize-based systems, determined using the mean-conditional value at risk optimization model are given in Table B1 and Table B2 in the appendix.

3.2. *Rabi* crops profitability evaluation

The net return from different *rabi*/winter season crops varied significantly, owing to difference in productivity and crop specific market price (Fig. 5). The least net return of <50,000 INR ha^{-1} was observed under CT-winter maize and wheat (Fig. 5). In contrast, the highest net returns were observed for ZT-mustard and PB-mustard, averaging over 75,000 INR ha^{-1}. We used the net-return frontier for *rabi*/winter-season crop to determine the optimal land allocation for higher return, independent of *kharif* (rainy) season crop performance. However, it is equally important to consider the impact of the *rabi*/winter season crop on the risk-return tradeoff of *kharif* maize, and vice versa when adopting a systemic approach. We present a system level portfolio in the subsequent section. Through the mean-variance optimization model, we assessed whether there are preferred combinations for the *rabi* season. The frontier indicated that ZT-mustard emerges as the most profitable option, making it the choice for a risk-neutral farmer (as shown in Fig. 6). For mildly risk-averse farmers, a blend of ZT-winter maize and ZT-mustard is favored, with a suggested allocation of 70 % and 30 % of the land area, respectively. Meanwhile, those leaning towards being very risk-averse would find a mix of ZT-winter maize and CT-wheat as the preferred *rabi* crop, with recommended allocations of 34 % and 66 % of the total land area, respectively. The optimal weights obtained using the mean-conditional value at risk optimization model and are presented in Appendix B, Table B2.

While the combination of ZT-winter maize and mustard may be preferred by a mildly risk-averse farmer in the *rabi* season, it is important to note that they stand to benefit more in the *kharif* season, yielding returns of ~60,856 ha^{-1} (calculated as 0.7 × 58,639 + 0.3 × 61,807) with a standard deviation of about 37,085. This standard deviation is lower than the maximum *kharif* return on the higher risk side. However, using this portfolio in the *kharif* season would be suboptimal, as the returns from maize are less than the maximum return option for the *kharif* season (ZT-MCS), which yields about 62,950 INR at a significantly lower standard deviation of 30,300 INR. In the following section, we explore these seasonal tradeoffs by optimizing system net returns.

3.3. The cropping system productivity and profitability perspective

The net return differed significantly across the tillage and cropping system combinations (Fig. 7). Notably, ZT-MMuMb had the highest system net returns, although this was not significantly different from ZT-MCS, PB-MMuMb, and PB-MCS systems. Conversely, net returns under conventional tillage practices hovered around ~100,000 INR ha^{-1}, significantly lower than those achieved under ZT and PB treatments. This can be attributed to the additional costs associated with tillage (Fig. 7). In a system portfolio assessment (Fig. 8), we observed that, regardless of risk preference (whether being profit-oriented or risk-averse), the treatments on the frontier include ZT-MMuMb, PB-MWMb, ZT-MMS, and CT-MMS. Furthermore, some risk-averse farmers could potentially benefit from diversified systems by allocating a portion of their land to ZT-MMuMb and PB-MWMb (at 54 % and 46 % allocation) to target a return of INR ~1,32,000 ha^{-1}, or to ZT-MMS and PB-MWMb (at 55 % and 45 % allocation) to target a return of INR ~1,22,000 ha^{-1}, or to ZT-MMS and CT-MMS (at 51 % and 49 % allocation) targeting return of INR ~1,06,000 ha^{-1}. The optimal weights

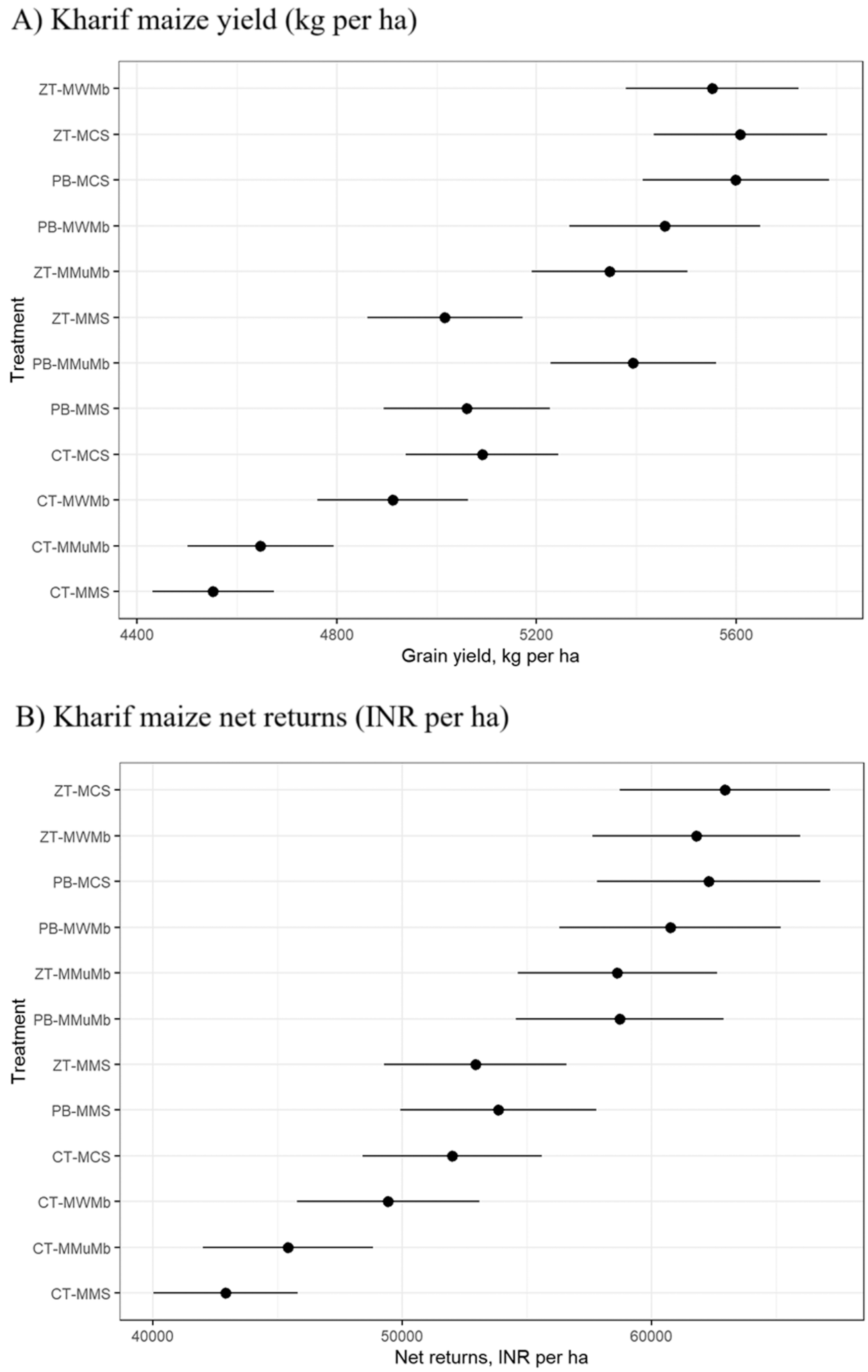

Fig. 2. The average productivity (kg ha^{-1}) (a) and profitability (INR ha^{-1}) (b) (represented by the dot) and their inter-temporal variation (95 % confidence interval limits, 1.96+/- standard error) during the 14-year long-term experiment among different tillage and cropping system combinations. CT: Conventional tillage, ZT: Zero tillage, PB: Bed planting, MWMb: Maize-wheat-mungbean system, MMuMb: Maize-mustard-mungbean, MCS: Maize-chickpea-*Sesbania*, MMS: Maize-maize-*Sesbania* system.

determined using the mean-conditional value at risk optimization model is presented in Table B3 in Appendix B.

4. Discussion

4.1. Differential productivity outcome and risk-return trade-offs of maize based diversified CA systems

Crop diversification stands as an important component within conservation agriculture systems, widely due to its risk transfer or adaptation strategies for production, market, and climate-related risks (Birthal and Hazrana, 2019; Mzyece and Ng'ombe, 2021). Based on crop component of a cropping system, each cropping systems has distinct advantages either for productivity, profitability, or yield stability (Beillouin et al., 2019), thereby leading to distinct risk-return trade-offs. Additionally, beyond diversification, other facets of CA, such as minimum tillage and soil cover play crucial role in enhancing soil health and crop productivity. As a reult these practices are instrumental in maximizing returns while mitigating risks stemming from external production shocks (Giller et al., 2015) and in altering the overall risk-return trade-offs (Hurley et al., 2018; Hauk et al., 2017).

Thus, to address how optimal land allocation should occur among

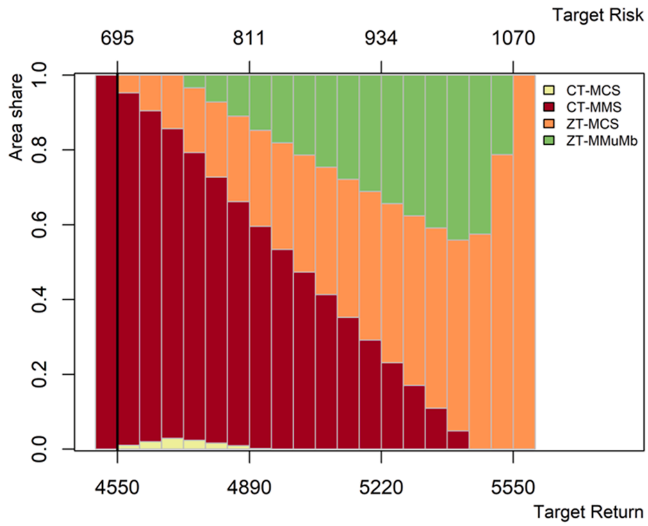

Fig. 3. *Kharif* maize yield (kg ha^{-1}) frontier showing optimal land allocation to different tillage and cropping system combination with specific targeted return (Primary x-axis), standard deviation of return (Secondary x-axis), ordered by risk aversion profile. **Note:** The scenarios are hypothetical for all possible combinations of risk averse and risk neutral decision makers. Going along x-axis (from left to right) lists different combinations of cropping systems with higher return as well as higher risk. Extreme left (less risk), extreme right (more return). CT: Conventional tillage, ZT: Zero tillage, PB: Bed planting, MWMb: Maize-wheat-mungbean system, MMuMb: Maize-mustard-mungbean, MCS: Maize-chickpea-*Sesbania*, MMS: Maize-maize-*Sesbania* system.

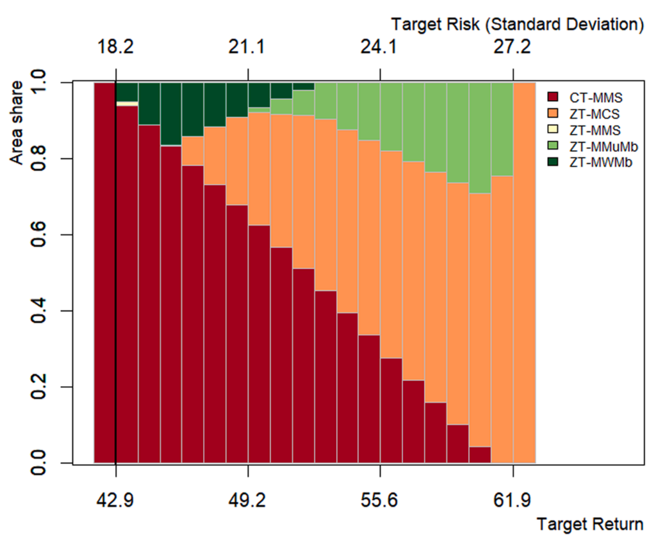

Fig. 4. *Kharif* maize profit (INR ha^{-1}) frontier showing optimal land allocation to different tillage and cropping system combination with specific targeted return (Primary x-axis), standard deviation of return (Secondary x-axis), ordered by risk aversion profile. **Note:** The scenarios are hypothetical for all possible combinations of risk averse and risk neutral decision makers. Going along x-axis (from left to right) lists different combinations of cropping systems with higher return as well as higher risk. Extreme left (less risk), extreme right (more return). CT: Conventional tillage, ZT: Zero tillage, PB: Bed planting, MWMb: Maize-wheat-mungbean system, MMuMb: Maize-mustard-mungbean, MCS: Maize-chickpea-*Sesbania*, MMS: Maize-maize-*Sesbania* system.

various cropping systems to achieve specific targeted yield or profitability at designated levels of risk, the study employed modern portfolio theory and quadratic optimization techniques (as proposed by Sukcharoen and Leatham, 2016) to find treatment combinations that may not have been initially considered. For example, at system level ~20 % land area under PB-MWMb and rest in ZT-MMuMb can generate ~14, 000 INR more return as compared to ~10 % area under PB-MWMb and rest under ZT-MMS. It is specifically important for an on-station long term trials to do similar risk assessments to suggest alternatives that consider all possible farmer profiles (from very risk averse to risk neutral) and all possible options, the farmers can opt, or the cropping system prevalent in the geography (Khedwal et al., 2023) and thereby providing results that may be applicable in real world on-farm conditions. The farmers in the North-western Indo-Gangetic plains are more progressive and do farming for generating more profit. Under such condition a more profit generating combinations can be opted. However, if a region is dominated by small holder farmers, with less risk-taking ability, as in Eastern India, a less risky combinations can be advised. Moreover, our study's comparison of cropping systems revealed distinct yield and profitability outcomes over the long run, showcasing varied risk-return profiles (as depicted in Figs. 2 and 4). This highlights the significance of considering not only productivity and profitability but also the associated risk factors when making decisions about cropping system choices and land allocation.

Soil mediated changes are considered as major pathway for outcomes associated with crop diversification. The specific combinations of crops within a cropping system exert a pronounced influence on various soil properties, the prevalence of soil microorganisms, biological fertility, and the soil's capacity to supply nutrients (McDaniel et al., 2014). For instance, integrating double legumes such as Chickpea and *Sesbania* into the cereal system, as seen in the MCS system, leads to long-term improvements in soil fertility, thereby supporting higher crop productivity within this system (Parihar et al., 2016a). Conversely, the inclusion of double cereals with substantial additional nitrogen input fails to enhance soil health and does not support higher yield (Parihar et al., 2016a, 2018a). Moreover, integrating mustard in the winter season and mungbean in the summer season contribute significantly to the system's profitability. Consequently, the MMS system featuring double maize exhibits stable yet lower yield, presenting an attractive option for risk-averse farmers. This system, when considered alongside the MCS and MMuMb systems, which support higher productivity and profitability regardless of tillage practices, serves as an ideal choice for farmers aiming for higher returns. While considering the combinations, in general CA-based tillage practices had higher return by ~43,000 INR than CT-based tillage practices, as aligned with a more significant changes in soil properties due to tillage practices than cropping system (Figs. 2,5,7).

In addition to considering risk aversion, it's crucial to prioritize which crop and season the farmer intends to focus on. For example, a risk-neutral farmer primarily concerned with *kharif* maize might find the ZT-MCS strategy optimal. However, this approach might not align with the maximum return portfolio for overall system net returns, which might consist of ZT-MMuMb exclusively or other optimal strategies for a risk-averse farmer. Consequently, economically speaking, the farmer could miss out a less risky yet more profitable system alternative. Nevertheless, adopting these combinations can pose challenges for farmers with small landholdings, given the multiple constraints they face, including soil conditions and weather variations. In certain places, the soil hydrology and landscape may not support crop diversification. In tandem with the strategy of crop diversification, it's vital to consider the antagonistic interaction, such as pest and disease profiles, among neighbouring crops before formulating recommendations. Additionally, recommendations for optimal land allocation must account for local-level price risks (Rosa et al., 2019).

Despite these practical constraints, leveraging modern portfolio theory to optimize long-term experimental data holds promise in bridging these experiments with climate adaptive policies. For instance, in Europe, Roche and McQuinn (2004) demonstrated how modern portfolio theory could inform the Common Agricultural Policy to encourage farmers to adopt riskier but more resource-efficient technologies. Similarly, considering the environmental advantages of zero

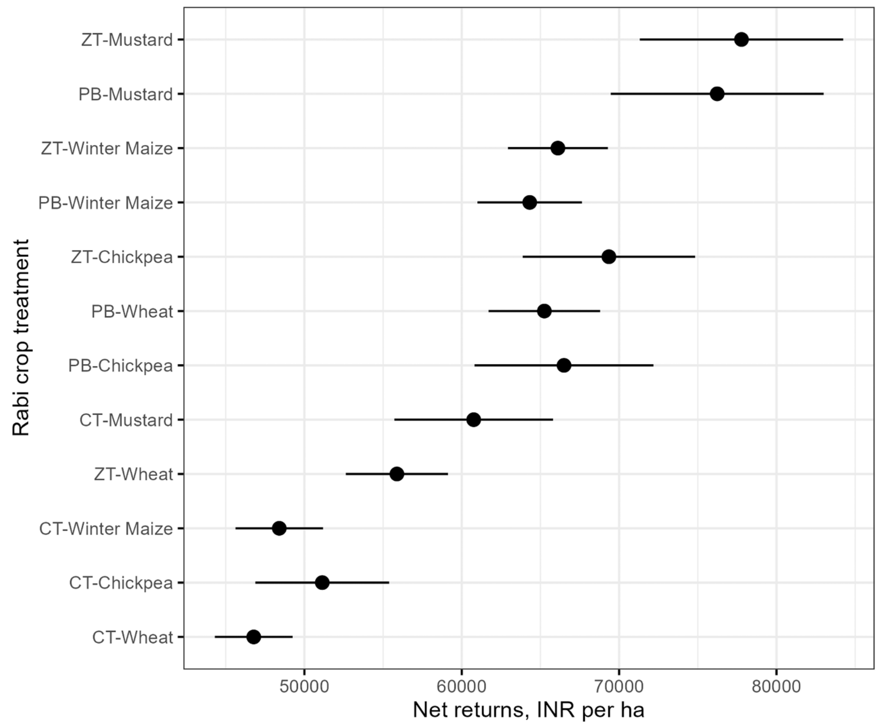

Fig. 5. The average profitability of winter season crop (represented by the dot) and their inter-temporal variation (95 % confidence interval limits, 1.96+/- standard error) during the 14-year long-term experiment among different tillage and cropping system combinations. CT: Conventional tillage, ZT: Zero tillage, PB: Bed Planting.

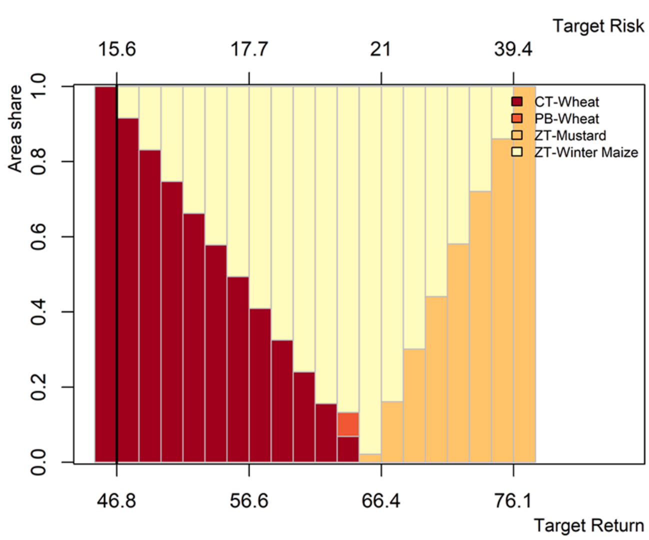

Fig. 6. *Rabi* crops net return frontier (in INR ha^{-1}) showing optimal land allocation to different tillage and cropping system combinations with specific targeted return, standard deviation of return, ordered by risk aversion profile. **Note:** The scenarios are hypothetical for all possible combinations of risk averse and risk neutral decision makers. Please refer caption of Figs. 3 and 4.

tillage practices, the risk-return tradeoffs we have identified could aid in determining incentives necessary to encourage farmers to adopt riskier yet environmentally friendly cropping systems, as evident in studies by Castro et al. (2013), (2015). The results derived from this type of analysis can inform decisions beyond the long-term experiment trial locations with similar biophysical conditions and cropping system performance in terms of intertemporal variability. Whereas in a newer region where weather and other biophysical risk affects the cropping system performance differentially, the proposed methods can be used to find newer risk proof cropping system combinations.

4.2. Limitations and future research

The mean-variance analysis suffers from a notable limitation as it solely focuses on two moments of the distribution (mean and variance), potentially overlooking the significance of other moments. Conducting a comprehensive whole-distribution analysis, especially using stochastic dominance, could provide deeper insights, particularly if connected to farmers' risk aversion levels. This notion is underscored in the study by Hurley et al. (2018), which examined how weather risks might influence the assessment of agricultural technologies' benefits. In appendices, we illustrate, through cumulative distribution functions, that the insights derived from mean-variance analysis align with comparisons of cumulative distribution functions.

Another limitation arises in measuring risk solely as inter-temporal standard deviation, whereas farmers might be more concerned about downside risk, particularly below a specific yield level. Determining this target yield level as priori remains challenging when using experimental data. Hence, we relied on inter-temporal standard deviation. However, other studies have explored the mean-expected shortfall analysis to address this limitation (e.g., Sukcharoen and Leatham, 2016). We incorporated this approach and found similar results for portfolios with the highest return and lowest risk, albeit slight differences emerged for portfolios reflecting mild risk aversion.

The final limitation pertains to the lack of identification regarding the sources of intertemporal variability. While we can pinpoint combinations with outcomes considered risky or less risky, our analysis doesn't explicitly identify the origins of this variability. A more detailed attribution analysis of risk, considering both climate and management variability, can enhance the understanding of the outcomes of risk-return trade-offs. We therefore do not consider the endogeneity of input use and influence of external risk factors directly. The outcome-based risk assessment approach we use allows us to only choose treatments robust to risk without specifying the source of the risk. Future

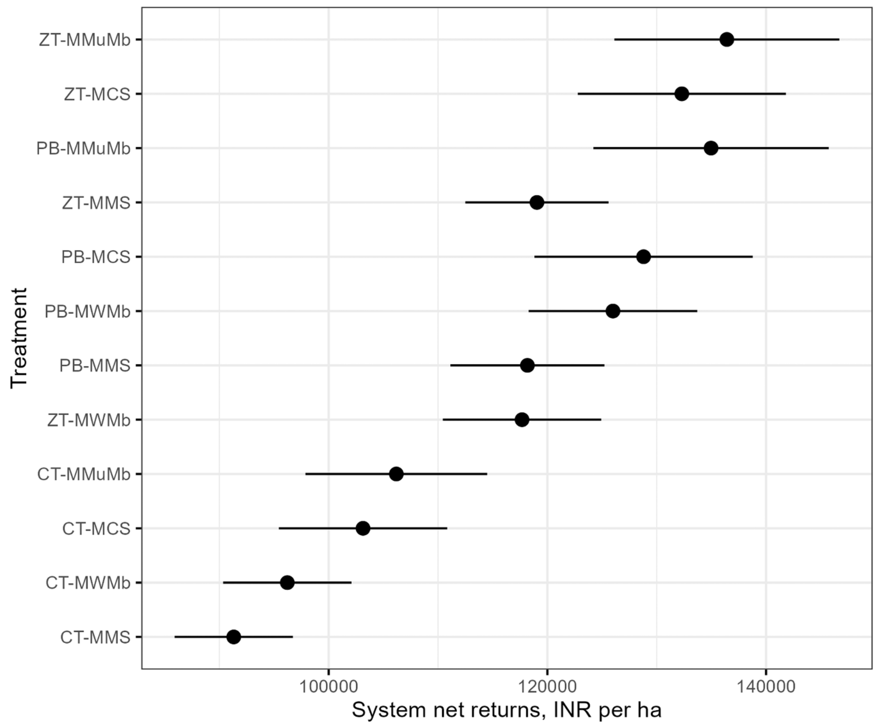

Fig. 7. The average net return (in INR ha^{-1}) of different tillage and cropping system combinations (represented by the dot) and their inter-temporal variation (confidence interval) during the 14-years of long-term experiment. CT: Conventional tillage, ZT: Zero tillage, PB: Bed planting, MWMb: Maize-wheat-mungbean system, MMuMb: Maize-mustard-mungbean, MCS: Maize-chickpea-*Sesbania*, MMS: Maize-maize-*Sesbania* system.

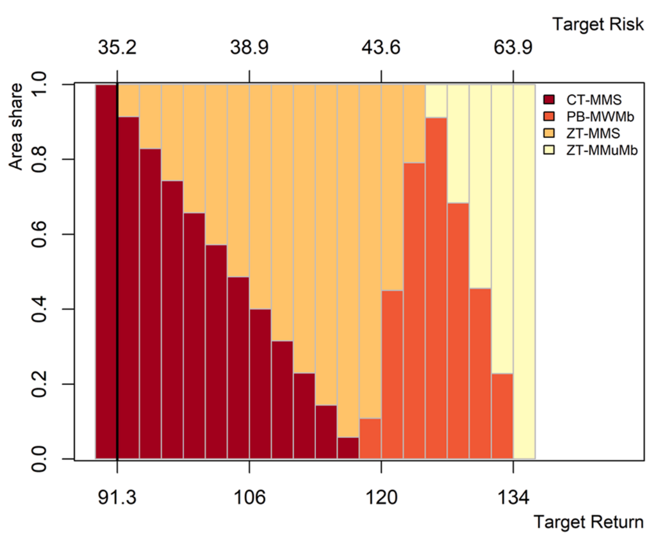

Fig. 8. System net returns frontier (rupees ha^{-1}) showing optimal land allocation to different tillage and cropping system combination with specific targeted return, standard deviation of return, ordered by risk aversion profile. **Note:** Target return and target risk (or standard deviation) are in thousand INR ha^{-1}. The scenarios are hypothetical for all possible combinations of risk averse and risk neutral decision makers. Please refer caption of Figs. 3 and 4.

analyses using the moments approach (e.g., Antle, 2010) could enable investigations into the specific sources contributing to the observed risk dynamics.

5. Conclusion

Maize based diversified systems under conservation agriculture have emerged as promising climate-adaptive alternatives to the conventional rice-wheat cropping systems prevalent in north-western India. While previous analyses of long-term experiments in this region have predominantly focused on yield gains, profitability, and environmental sustainability; the risk considerations have been largely overlooked. This paper looks at risk return trade-off by integrating risk considerations using mean-variance and mean-conditional value at risk (CVaR) optimization models. This aspect represents a significant contribution, filling a crucial gap in prior studies (e.g., Parihar et al., 2016).

The optimization modeling approach outlined in this study holds profound importance, not only for delineating optimal portfolios of maize-based diversified cropping systems and corresponding tillage practices but also for designing future long-term experiments and subsidiary or derivative experiments aimed at testing these optimal portfolios. This can be done by eliminating the treatments that had worse results for both returns and risk as well as including the optimal treatment combinations in any new long-term experiments.

Our findings highlight a tangible risk-return trade-off within maize based diversified cropping systems and tillage practices, particularly in scenarios with high profitability involving zero tillage (ZT) and bed planting (PB) practices, which exhibit high intertemporal variability (risk). The outcomes reveal that a risk-neutral farmer would find it optimal to adopt ZT-MMuMb. However, mildly risk-averse farmers would lean towards adopting combinations such as ZT-MMuMb and PB-MWMb, ZT-MMS and PB-MWMb, or ZT-MMS and CT-MMS. Meanwhile, a very risk-averse farmer would prefer the CT-MMS approach. These results underline the necessity of addressing intertemporal variability, particularly in ZT and PB based establishment practices (e.g., with chickpea), if predominantly risk-averse farmers are to consider adopting ZT and PB tillage practices. The optimization approach we have applied provides new combinations of diversified cropping systems that were not considered in previous analyses including partially applying the treatments on a smaller portion of land instead of the treatment that gives maximum returns on average. This method can be used in other on-farm applications, including for example variety diversification, and planting date diversification.

CRediT authorship contribution statement

Hari Sankar Nayak: Writing – review & editing, Writing – original draft, Investigation. **Maxwell Mkondiwa:** Writing – original draft, Formal analysis. Conceptualization, Methodology. **Kiranmoy Patra:** Writing – review & editing. **Ayan Sarkar:** Writing – review & editing. **K. Srikanth Reddy:** Writing – review & editing, Formal analysis. **Pramod Kumar:** Writing – review & editing, Formal analysis. **Sneha Bharadwaj:** Writing – review & editing. **Rajbir Singh:** Writing – review & editing. **CHITER MAL PARIHAR:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127436.

Data availability

Data will be made available on request.

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