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RESEARCH PAPER

Characterization of herbicide use pattern and factors responsible for herbicide resistance against *Phalaris minor* in wheat (*Triticum aestivum* L.) in north–western, India

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Abstract
Herbicide resistance has become one of the major unsustainability issues of the worlds' largest wheat (*Triticum aestivum* L.) ecosystems. In wheat, there is problem of herbicide resistance in *Phalaris minor*. *Phalaris minor* can cause wheat yield loss of 10–50% depending upon the density. We therefore, aimed to characterize herbicide use pattern and the factors responsible for the development of herbicide resistance against *Phalaris minor* in wheat based on data recording from 250 wheat growers of two contrasting agro-ecological regions viz. Bathinda (in south-western) and Rupnagar (in sub-mountainous), Punjab in north–western India. These results revealed that ~ 80–83% of respondent were using clodinafop, sulfosulfuron and pinoxaden herbicides against *P*. *minor*. On an average, farmers were applying 1.87-times of x-dose of total herbicides, but still getting only 70–82% control of *P. minor*. Albeit of perceived resistance, clodinafop was the most preferred herbicide against *P. minor*. The developed binary logistic regression model revealed that besides consistent application of herbicides of same mode of action, cultural variables viz. conservational method of sowing (zero tillage), time to first irrigation after sowing (< 24 days), days to reach field capacity moisture within 10 days and crop rotation followed were elucidated as a significant ($p < 0.05$) determinants of problem of herbicide resistance encountered by farmers. About 95.6% of farmers were using less water (225–300 L ha^{-1}) and flood jet or hollow cone nozzles against the recommended practices (375 L ha^{-1} water and flat fan nozzle), therefore, contribute significantly towards the development of herbicide resistance against *P. minor* in wheat. Additionally, ~ 74% farmers followed delayed herbicide application against recommended time (30–35 days after sowing), which resulted in reduced efficacy of applied herbicides. About 75.6% respondents perceived poor quality of herbicides as prime cause for ineffectiveness of applied herbicides, while others believed that mono-cropping and over/under-dose of applied herbicides contributed to the evolution of resistance in *P*. *minor*. The 'β' coefficient values ($\text{Exp}(\beta) = 0.754$) of Logit model developed revealed that if farmers follow crop rotation, there are ~ 75.4% chances of decreased herbicide resistance in *P. minor*. Similarly, the farmers' who apply first irrigation within first 24 days after sowing have ~ 2.67-times higher chances of escaping the herbicide resistance, compared with those where first irrigation to crop is delayed ($\text{Exp}(\beta) = 2.674$). Therefore, addressing the complexities surrounding herbicide resistance in wheat ecosystems necessitates a multifaceted approach that integrates cultural practices, judicious herbicide application, and adherence to recommended agronomic techniques, such as crop rotation and timely irrigation, to effectively mitigate the evolution of resistance in *P. minor*.

Keywords Herbicide resistance · Spray technology · *Phalaris minor* · Binary logistic regression · South-western Punjab · Sub-mountainous region · Wheat

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Introduction

Wheat (*Triticum aestivum* L.) belongs to family *Poaceae*, and has been the major cereal crop cultivated across the globe to provide staple food for ~ 1/5th of the world population and to meet ~ 20% of the global calories and proteins intake of humankind. Worldwide, wheat occupies ~ 219 million hectares (Mha) with production and productivity of ~ 761 million tons and 3,474 kg ha^{-1} wheat grains, respectively (FAOSTAT 2021). In India, wheat occupies ~ 14.3% of the total cultivable area in the world with production and productivity of ~ 1.8 million tons and 3,431 kg ha^{-1}, respectively (Soni et al. 2023). Wheat has been the most predominant crop cultivated extensively across the north–western Indo-Gangetic Plains (IGPs) including states of Punjab, Haryana and Uttar Pradesh with a production of ~ 63.3 million tons from ~ 16 Mha area (Bhatt et al. 2019, 2021). Over the last two decades, sustainability of wheat ecosystems has been challenged by declining underground water tables (Bhatt et al. 2019, 2023; Avtar-Singh et al. 2024), crop residues burning (Singh et al. 2020; Sharma et al. 2021), large emissions of greenhouse gases (Singh et al. 2020), high energy and carbon footprints (Singh et al. 2021a, 2019; Kaur et al. 2024), besides moderate to severe infestation of weeds which significantly influences the productivity and economic returns to the farmers in north–western India (Singh et al. 1999; Chhokar et al. 2008; Sidhu et al. 2014).

Before green revolution, weeds were not the major problem in wheat because of inherent better competing ability of tall wheat varieties, and also because the annual broadleaf weeds were relatively less aggressive in nature (Chhokar et al. 2012; Dhanda et al. 2022). However, with the introduction of semi-dwarf varieties of wheat, the problem of *P. minor* was aggravated, because semi-dwarf varieties required frequent irrigations and higher fertilizer doses as compared to native tall wheat varieties that contributing in developing an ecosystem that was more favorable for the growth and development of *P. minor* (Singh et al. 1999; Chhokar and Sharma 2008). Further, the mimicry nature of *P. minor* makes it difficult to identify and rogue out it from crop plants. Weeds are one of the major causes for lower yields; productivity decline by 15–40% or more besides reducing the produce quality (Singh et al. 1999). *Phalaris minor* density of 60–70 plants m^{-2} reduces the wheat yields by ~ 10% (Malik and Singh 1995), and a loss may reach upto ~ 50% if the densityincreases to 500 plants m^{-2} (Soni et al. 2023). Earlier research underpins that wheat yield loss is brought on by plant population of *P. minor* at 2000–3000 plants m^{-2} (Malik and Singh 1995). Weeds predominately affect wheat yield by reducing the number of effective tillers, grains per spike and 1000-grain weight (Sarwar et al. 2013). Therefore, there exists a vast scope to enhance the productivity through better management techniques (including weed management), as there is discrepancy between the yield potential of high yielding varieties and the yield that farmers are now realizing in their fields (Evans and Fischer 1993; Espe et al. 2016).

The IGPs of north–western India mainly comprises rice–wheat cropping system, which is considered responsible for moderate to severe infestation of *P. minor* (Soni et al. 2023). Nonetheless, *P. minor* being morphologically similar to wheat plants, particularly during its vegetative phase, therefore, gets escaped from manual weeding, and thereby leaving the only option of herbicidal control (Chhokar et al. 2008). Besides its morphological similarity with wheat, its seed shedding behavior (which matures earlier than wheat) and germination in multiple flushes makes it a most difficult weed to control in wheat (Sidhu et al. 2014; Rana and Rana 2015). The continuous build-up of resistance in *P. minor* to herbicides has raised serious sustainability concern related to resiliance of rice–wheat cropping system across the north–western IGPs (Chhokar et al. 2018; Chaudhary et al. 2021).

Globally, 266 weed species comprising 153 dicots and 113 monocots are resistant to 21 out of 31 herbicide sites of action based on a total of 530 unique instances of herbicide resistance recorded (Singh et al. 2021d; Heap 2022). Recent reports confirmed resistant weed species in 95 crops across 71 countries (Heap 2022). In India, maximum use of herbicides is in rice, wheat and soybean, therefore, these ecosystems are facing severe problems of herbicide resistance (Chhokar et al. 2018). During early 1980s, farmers started using herbicides with three modes of action; acetyl-coenzyme A carboxylase (ACCase), acetolactate synthase (ALS) and photosystem II (PS II) inhibitors against *P. minor* infestation (Chhokar and Sharma 2008), and experienced highly effective control in the entire north–western IGPs. Considering highly effective control, farmers started spraying these group of herbicides continuously in rice–wheat cropping system. However, its application at more than the recommended dose started in late 1990s onward (Yadav and Malik 2005). Following the initial report of herbicide resistance in India, the resistance area in the country's north–western region reached up to 0.8–1.0 Mha (Malik and Singh 1995) with Haryana (0.56–0.6 Mha) and the Punjab (0.3 Mha) states experienced the worst impacts (Franke 2002). A recent report revealed that *P. minor* infested ~ 15 Mha in 2019, which comprises ~ 50% of the total wheat-cultivated land in the north–western IGPs (Soni et al. 2023).

During 1997–98, farmers started using alternate herbicides e.g., clodinafop, sulfosulfuron and fenoxaprop to manage resistant population of *P. minor* (Yadav and Malik 2005). Nevertheless, the practice of tank mix applications of post-emergence herbicides with metribuzin and its application alongwith urea fertilizer just 2–3 days after first irrigation gained ground in the entire north–western India (Soni et al. 2023). But, within just 10–15 years, these herbicides lost their efficacy. Farmers were compelled for either doubling the rate of herbicide application and/or repeat the sprays for effective control of *P. minor* (Bhullar et al. 2014; Soni et al. 2023). Numerous investigations have demonstrated that *P. minor* has developed multiple herbicide resistance through different mechanisms of action viz. suppression of acetolactate synthase, photosynthesis at the photosystem-II site A, and acetyl-CoA carboxylase (ACCase) (Chhokar et al. 2008; Yadav et al. 2016; Punia et al. 2017).

The majority of weeds are becoming more prevalent as a result of changing global climate, which also affects their dynamics, life cycle and pressure from infestations and general occurrence. According to Olson et al. (2000), climate change causes irregularities in the pattern of rainfall, wind, relative humidity, and soil/air temperature, which could reduce spray coverage or retention times of active chemicals after their application (Olson et al. 2000). Climate change alters weed populations, their behavior i.e. how they interact with crops and the chemical methods used to control them (McDonald et al. 2009; Blumenthal et al. 2013; Varanasi et al. 2015). The effectiveness of applying pre-and post-emergence herbicides to crops may reduce under climate changing scenario (Varanasi et al. 2015). The dry cuticle of leaves thickens under water stressed condition make them more difficult to control with the use of post-emergence herbicides than plants that are actively growing. The herbicides that are absorbed by plant roots (eg. pre-emergence herbicides) need adequate soil moisture and actively growing roots to reach their target sites. Conversely, the efficiency of pre-emergence herbicides is reduced in conditions of drought (Amare 2016). It is reported that a change in temperature increases the incidence of metabolism-based reduced herbicide efficacy on weeds and therefore, increases the risk for evolution of non-target site herbicide resistance (Matzrafi et al. 2016).

Presently, numerous reports indicates that continuous rice–wheat cropping and using same group of herbicides year after year favor *P. minor* growth and development with negative consequences on wheat productivity, but these are arbitrary and vague (Punia et al. 2013; Bhullar et al. 2014). There exist other factors which are also considered responsible for the development of resistance in *P. minor*. The present study was therefore, conducted to overview of the reasons responsible for the build-up of herbicide resistance in *P. minor* at farmers' field. Considering the fact that weed flora also changes with temperature, rainfall, humidity and soil conditions, we extrapolate the present study in two contrasting regions viz. south-western and sub-mountainous Punjab in north–western India (Fig. 1). We evaluated and compared the factors responsible for the development of resistance against herbicides application for the control of *P. minor*. We hypothesized that the differences in cropping systems would lead to differential impact on weed seed bank, weed flora and the herbicide use pattern and would variably impacts the resistance of *P. minor* against herbicide application. The development of herbicide resistance in *P. minor* varies between contrasting regions, specifically the south-western and sub-mountainous areas of Punjab, north–western India. This variability is attributed to distinct environmental conditions, agronomic practices and weed management strategies prevalent in each region. The hypothesis posits that factors such as climate variability, soil characteristics, cropping patterns, and herbicide usage patterns significantly influence the emergence and spread of herbicide resistance in *P. minor*. The present study was therefore conducted to assess and compare the prevalence and severity of herbicide resistance in *P. minor* populations between the south-western and sub-mountainous regions of Punjab, in north–western India and to investigate the influence of cropping systems and agronomic practices, such as crop rotation and tillage practices, on the dynamics of herbicide resistance in *P. minor*. More specifically, we evaluated the efficacy of different herbicide application strategies and their long-term effects on the evolution of herbicide resistance in *P. minor* and to identify novel weed management approaches and integrated strategies for mitigating herbicide resistance, tailored to the specific agro-ecological conditions of each study region.

Materials and methods

Brief description about study region

The present study was conducted in Rupnagar district in sub-montainous region and Bathinda district in south-western Punjab, a north–western state of India. Geographically, Rupnagar is situated in the eastern portion of Punjab between latitudes of 76° 19′00″ and 76° 45′00″ N and longitudes of 30° 44′00″ and 31° 25′00″ E (CGWB 2015). Rupnagar district has a geographical area of ~ 1440 km^2 and is bounded by Himachal Pradesh in the north and north-east, Hoshiarpur, Nawanshaher (Shahed Bhagat Singh Nagar) and Ludhiana district in the west, Fatehgarh Sahib district in the South and the Mohali district in the south east (CGWB 2015). Rupnagar district has five administrative blocks namely Ropar, Nurpur Bedi, Sri Anandpur Sahib, Chamkaur Sahib and Morinda. The study region in sub-montaneous Punjab receives ~ 776 mm rainfall annually (in 41 days), of which a large chunk (~ 78%) is contributed by south-west *monsoon*. The climate of the district can be classified as tropical steppe hot and semi-arid type. Conversely, Bathinda district has less rainfall

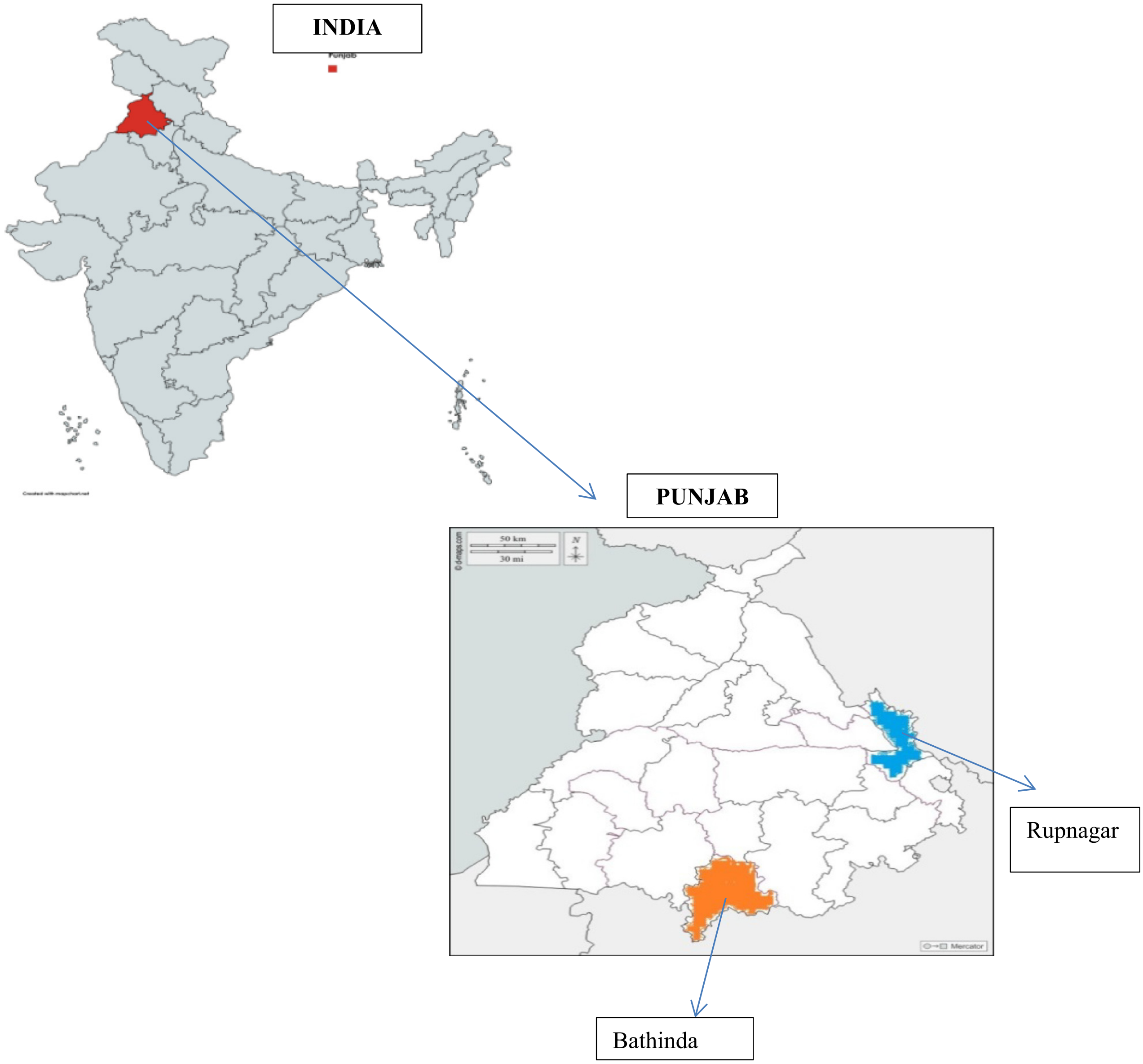

Fig. 1 Location map of Punjab in India and Bathinda and Rupnagar districts in Punjab

(~ 408 mm in just 20 days), which is unevenly distributed over the entire district. The south-west *monsoon* sets in last week of June and withdrawn towards end of September, and contributes ~ 82% of total average annual rainfall. The remaining ~ 18% of the annual rainfall occurs during non-*monsoon* period of the year in the form of thunder storm and western disturbances (CGWB 2013). Bathinda district is situated in the southern part of Punjab State and lies between latitude of 29° 33′ and 30° 36′ N and longitude of 74° 38′ and 75° 46′ E (Topo sheets No. 44J, 44K, 44N, and 44O). The district covers an area ~ 3367 km^2 in seven administrative blocks viz. Bathinda, Nathana, Rampura, Phool, Talwandi Sabo, Sangat and Maur.

Data collection

Data regarding herbicides use pattern were recorded in personal interviews with the farmers during field surveys, and the information was recorded in semi-structured questionnaires. A pre-tested questionnaire was used for data recording from 250 wheat growers in a systematic field survey conducted during *rabi* season of 2022–23 in two districts (Bathinda and Rupnagar). An interview schedule was designed to gather information regarding kind and nature of weed flora, their infestation severity, weed population density, weed control (pre-and post-emergence herbicides application) measures followed and their weed control efficacy. In addition, respondents were asked about the spray technology followed, e.g., sprayer type (knapsack vs. power sprayer), nozzle type (flat fan vs. flood jet/cone type), volume of water applied for herbicide application etc. The information regarding wheat grain yield was recorded at harvesting. At each field, farmers were advised to harvest sub-plots (4 × 4 m) randomly at two sites, and the yield of two sites per field was pooled to estimate grain yield (expressed as q ha^{-1}). We gathered information regarding sowing methods, days after first irrigation applied to wheat, days for attaining field capacity moisture, continuity of a cropping system etc. with likely impact on development of herbicide resistance was also recorded. Farmers perceived weed control efficiency based on effectiveness of weed control against applied herbicides during the previous years. However, to ascertain efficacy of applied herbicides, fields of 20 randomly selected famers (2 fields per administrative block per district/region) were visited during different crop growth phases.

These two districts were selected purposively to account for variation in herbicides use pattern, differences in cropping systems and the prevailing weather conditions. The respondents were randomly selected from different villages of five administrative blocks each district. In each block, five villages were selected (Table 1). In order to ensure the representativeness and robustness of data collected during the field survey, a meticulous approach was undertaken for the selection of villages and respondents. The districts of Bathinda and Rupnagar were purposefully chosen to encapsulate the spectrum of herbicide use patterns, cropping systems, and prevailing climatic conditions within the region. Within each district, a systematic methodology was employed to select villages, taking into consideration factors such as geographical dispersion and the diversity of agricultural practices. Specifically, five administrative blocks were identified in each district to provide comprehensive coverage of the respective agricultural landscapes. Subsequently, five villages were randomly selected from each block, ensuring a balanced representation across different geographical areas and cropping systems. To minimize bias, respondents were selected through random sampling within the chosen villages, thereby ensuring a fair and unbiased representation of wheat growers across the study area. This meticulous approach aimed to enhance the reliability and validity of the data collected, thereby facilitating a comprehensive analysis of herbicide use patterns and their associated factors in the target regions.

Data compilation, analysis and interpretation

The data collected from the farmers were organized and entered into Microsoft Excel Spreadsheets to facilitate classification and analysis. To identify the factors influencing the likelihood of herbicide resistance, we employed the binary logistic regression model, a statistical technique widely recognized for its efficacy in analyzing categorical outcomes (Zaidi and Luhayb 2023). This approach allowed us to assess the significance of various predictor variables in predicting the probability of herbicide resistance occurrence, thereby facilitating a nuanced understanding of the underlying dynamics. Additionally, to determine the relative importance of different factors contributing to poor herbicide efficacy, we adopted the ranking method developed by Henery Garrett (1969). It involves assigning ranks to each potential cause of poor efficacy based on its perceived impact or significance as perceived by the respondents. By employing

Table 1 Details of villages covered for data-set collection and the predominant cropping systems in Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India

Agro-climatic region/district	Administrative blocks	Villages covered	Predominant cropping system
South-western Punjab/Bathinda	Maur		Rice–wheat and cotton-wheat
	Sangat	Jai Singh Wala, Phullo Mithi, Pacca Kalan, Phallar	Rice–wheat and cotton-wheat
	Bathinda	Nahiyanwala, Mehma Sarja, Giddar, Khemuana, Jeeda	Rice–wheat
	Talwandi Sabo	Chathewala, Ramgarh Bhundar, Teona Pujara, Malkana, Bangi Nihal Singh	Rice–wheat and cotton-wheat
	Rampura	Poohla, Poohli, Sema, Bajjoana, Bhai Roopa	Rice–wheat
Sub-mountainous Punjab/Rupnagar	Ropar	Mahlan, Mansua, Jhallian, Suratput, Gurdaspura	Rice–wheat and maize-wheat
	Morinda	Dhangrali, Gopalpur, Maankheri, Kajauli, Boothgarh	Rice–wheat
	Chamkaur Sahib	Hafizabad, Fatehpur, Mehtot, Behrampur bet, Khokhar	Rice–wheat and maize-wheat
	Nurpur Bedi	Asaltpur, Aulakh, Musapur, Gusemajra, Nangal ambian	Rice–wheat and maize-wheat
	Sri Anandpur Sahib	Aggampur, Dasgrain, Jindbarri, Surewal, Bhaowal	Maize-wheat

this methodology, we were able to systematically order the causes of poor herbicide efficacy, thereby prioritizing areas for further investigation or intervention. The utilization of Henery Garrett's ranking method provided a structured and transparent approach to discerning the most influential factors contributing to suboptimal herbicide performance in agricultural settings.

Binary logistic regression model

Since our result is binary, i.e. either the farmer encountered the problem (1) or not (0), linear regression models are effective when the dependent variable is of continuous type (Singh et al. 2021c). Therefore, it was determined that the binary logistic regression model was the most suitable model, because a logistic regression gives a transformed value based on the independent variable, Logit (*p*) (Eq. 1–3).

$$\text{Logit (p)} = \ln p/(1-p) = \ln \text{(odds ratio)} \quad (1)$$

$$Prob(Yi = 1) = Pi = F(Zi) = F(\propto + \sum \beta iXi) = \frac{1}{1 + e - Zi} \quad (2)$$

$$Prob(Yi = 0) = 1 - Prob(Yi = 1) = (1 - Pi) = \frac{1}{1 + e - Zi} \quad (3)$$

where, '*p*' is the probabilities of facing the problem of herbicide resistance and '*1−p*' not encountered it, and an odds ratio is the ratio of two probabilities '*p*/(1−*p*)' and farmer participated in extension program, 'X_i' represents explanatory variables (Table 2), and 'α' and 'β' are parameters to be estimated. Logistic regression transforms the linear regression equation using the logit function, which maps the probability of the outcome variable to the range of real numbers. The logistic regression model estimates the coefficients of the predictor variables that maximize the likelihood of observing the given outcome data. The estimation is typically performed using optimization techniques such as maximum likelihood estimation. By solving, Eqs. 2 and 3, we get Eq. 4.

$$\frac{Prob(Yi = 1)}{Prob(Yi = 0)} = \frac{Pi}{1 - Pi} = eZi \quad (4)$$

where, '*Pi*' is the probability that '*Yi*' takes the value 1 and then (1 − *Pi*) is the probability that '*Yi*' is '0' and 'e' is the exponential constant, and by taking the natural log of both sides of Eq. 4, we get Eq. 5.

$$Zi = \ln\left(\frac{Pi}{1 - Pi}\right) = \beta 0 + \beta 1X1i + \beta 2X2i + \ldots + \beta kXki + ui \quad (5)$$

The general regression model including 14 variables is written below (Eq. 6).

Table 2 Independent variables included in the development of Logit model and descriptive statistics for predicting herbicide resistance against *P. minor* in wheat in different administrative blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. *Data pooled for two districts*

Variable	Variable	Transformation criteria for binary logistics model	Frequency (ύ)	
			1	0
Personal characteristics				
Land-holding	X_1	1 = up to 2 ha, 0 = > 2 ha	71 (28.4)[†]	179 (71.6)
Age of respondents	X_2	1 = up to 45 year, 0 = > 45 year	109 (43.6)	141 (56.4)
Education status	X_3	1 = up to 12th, 0 = above 12th	206 (82.4)	44 (17.6)
Lease status	X_4	1 = leased, 0 = own	158 (63.2)	92 (36.8)
Cultural characteristics				
Percent area under wheat	X_5	1 = > 75%, 0 = up to 75%	202 (80.8)	48 (19.2)
Sowing method	X_6	1 = conventional, 0 = rest	85 (34.0)	165 (66.0)
Days to field capacity moisture regime	X_7	1 = within 10 days, 0 = above 10 days	192 (76.8%)	58 (23.2)
First irrigation	X_8	1 = Timely (within 24 days after sowing), 0 = Delayed	64 (25.6)	186 (74.4)
Crop rotation followed	X_9	1 = Yes, 0 = No	26 (10.4)	224 (89.6)
Continuity of cropping system	X_{10}	1 = > 10 years only rice–wheat, 0 = rice/maize/cotton-wheat	118 (47.2)	132 (52.8)
Technology characteristics				
Herbicide spray (Pre/Post emergence)	X_{11}	1 = Post emergence, 0 = Pre-emergence	225 (90)	25 (10)
Sprayer type	X_{12}	1 = Knapsack, 0 = Power	191 (76.4)	59 (23.6)
Nozzle type	X_{13}	1 = Flat fan, 0 = rest	27 (10.8)	223 (89.2)
Volume of water applied	X_{14}	1 = 500 L ha^{-1}, 0 = rest	11 (4.4)	239 (95.6)

[†]Values in the parenthesis indicate % of respondents in each category

$$\text{logit}(p) = \ln p/(1-p) = \beta o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + \beta_{11} X_{11} + \beta_{12} X_{12} + \beta_{13} X_{13} + \beta_{14} X_{14} \quad (6)$$

where, 'β_i' and 'X_j' indicates 'i^{th}' coefficient and 'j^{th}' variable, 'X_{1-14}' indicates 14 variables included in the development of regression model (see Table 2 for details). Multi-collinearity was assessed between the independent variables prior to modeling using a Pearson correlation (r) value of > 0.7, a tolerance limit of 0.1, and a variance inflation factor (VIF) of > 5.0. Variables that didn't meet these requirements were taken out of the model to allow for more accurate conclusion-making. The Hosmer and Lemeshow test is used to determine the model's fitness; if '$p > 0.05$', the null hypothesis is accepted. If the predictor variable has a larger value, the Nagelkerke r-square better explains the variability in the dependent variable that is contributed by the predictor variable.

Selection of dependent and independent variables On the basis of dose applied and the percent control seen at each farmer's field, the dependent variable was categorized into two heads. It was considered that there was no significant problem with herbicide resistance if the farmer needed to apply the herbicide up to the recommended dose (0-×) of herbicide or achieve greater than 70% control up to double dose (> 1 to 2). Farmers who reported above 70% control even up to 2× were considered under the first category. This was due to inadequate spray technology (lower spray volume and inappropriate nozzle) or other limitation (trained workforce, lack of adequate moisture or poor field preparations etc.) on the ground. This fell short of the mark because of poor spray management and was only able to yield some concrete rather than results, some tangible conclusions rather than a general practice to recommend 2× to achieve 70% control or above. However, it was considered that issue of herbicide resistance (0) was present when a farmer required to apply more than 2×-times. There were a total of 14 independent variables in the regression model, divided into three categories i.e. (i) personal characteristics (size of land holding, age of respondents, education status, lease status), (ii) cultural characteristics (percent area under wheat cultivation, sowing method, days to field capacity moisture regime, first irrigation, crop rotation followed, continuity of cropping system), and (iii) technology characteristics (Herbicide spray (pre/post emergence, sprayer type, nozzle type, volume of water applied) (Table 2).

Henery Garrett's rank technique The ranking method developed by Henery Garrett's (1969) was utilized to determine the cause of inadequate efficacy of applied herbicides. Seven factors responsible and important for the development of herbicidal resistance in wheat were identified based on expert's opinion which includes poor quality of herbicides, everything fine but now cannot get same results of herbicide application, faulty spray practices, delayed herbicide application, improper herbicide dose, soil type and the seed bank of previous crop harvest. The respondents were also asked to rank these seven factors between 1 and 7. Garrett's ranking technique was applied to analyze different factors affecting wheat yield in response to decreased herbicide efficacy caused due to the developed resistance against applied herbicides, and the percentage position was calculated by using Eq. 7.

$$\text{Percentage position} = \frac{100\left(R_{ij} - 0.5\right)}{N_j} \quad (7)$$

where, 'R_{ij}' denotes a rank given for 'i^{th}' variable (factor) by the 'j^{th}' farmer and 'N_j' denotes number of variables (factors) ranked by the 'j^{th} ' farmer. A factor score was calculated by multiplying the number of farmers ranking different problems with their respective Garrett's values. Mean score for a problem was calculated by dividing the total score obtained by respective number of farmers. A factor with the highest mean score was given first rank, and the factor with the next highest mean score was given second rank and so on.

Economic and production efficiency

Average cost of cash inputs (ACCI) was estimated as a sum of expenditure incurred for the purchase of cash inputs (US\$ ha^{-1}; 1 US\$ = 80 INR) like diesel fuel, seed, chemical fertilizers (e.g. urea, DAP and muriate of potash), insecticides, fungicides and herbicides, and the labor cost for different field operations viz. fertilizer application and spray of plant protection chemicals etc. using Eq. 8.

$$\text{Average cost of cash inputs } \left(\text{US\$ ha}^{-1}\right)\left(\text{US\$ Mg}^{-1}\right) = 1, 2, 3, \ldots \text{n} \quad (8)$$

where, $C_{1,2,3,\ldots}$, represents cost for different inputs and labor cost.

The average gross returns (AGRs) were estimated as average grain yield (Mg ha^{-1}) for different blocks and average selling price (P) of 251.9 US\$ Mg^{-1} using Eq. 9.

$$Gross\ returns\left(AGRs, US\$ha^{-1}\right) = Average\ grain\ yield\left(Mgha^{-1}\right) \times Price\left(US\$Mg^{-1}\right) \quad (9)$$

The average net returns (ANRs) were estimated as a difference in AGRs and ACCIs using Eq. 10. The benefit-cost

(B, C) ratio was estimated as a ratio of AGRs and ACCIs using Eq. 11 (Singh et al. 2021a, 2021b).

$$Average\ net\ returns\left(ANRs, US\$\ ha^{-1}\right) = AGRs\left(US\$\ ha^{-1}\right) - ACCIs\left(\text{US\$ ha}^{-1}\right) \quad (10)$$

$$\text{Benefit} - \text{cost (B} - \text{C ratio)} = \frac{AGRs\left(US\$\ ha^{-1}\right)}{ACCI\left(US\$\ ha^{-1}\right)} \quad (11)$$

The production efficiency of wheat was estimated based on ratio of grain yield (kg ha^{-1}) and the average crop duration (in days; d) (Eq. 13). The economic efficiency was estimated as a ratio of GRs (US$ ha^{-1}) and the average crop duration (d) (Eq. 14) (Saini et al. 2019).

$$\text{Production efficiency}\left(\text{kg ha}^{-1}\text{d}^{-1}\right) = \frac{Total\ grain\ yield\left(kg\ ha^{-1}\right)}{Average\ crop\ duration(days, d)} \quad (13)$$

$$\text{Economic efficiency}\left(\text{kg ha}^{-1}\text{d}^{-1}\right) = \frac{Average\ gross\ returns\left(AGRs, US\$\ ha^{-1}\right)}{Average\ crop\ duration(days, d)} \quad (14)$$

Statistical analysis

Data were analyzed by the development of Logit regression model using the IBM SPSS 16.0. The parameters affecting the likelihood of herbicide resistance were found using the binary logistic model. Data were statistically analyzed for the comparison of mean values within administrative blocks of a region (south-western vs. sub-mountainous Punjab) by Least Significant Difference (LSD) Test at $p < 0.05$ using IBM SPSS 16.0 software. However, data on herbicide use pattern in two study regions was statistically analyzed using students' T-test at $p < 0.05$.

Results and discussion

Herbicides use pattern in different regions

Figure 2 illustrates the herbicide distribution pattern for the control of *P. minor* in wheat cultivation in south-western and sub-mountainous Punjab in north–western India. Farmers in the study region were using eight different herbicides viz. clodinafop, sulfosulfuron, pinoxaden, sulfosulfuron + metsulfuron, mesosulfuron + iodosulfuron, pendimethalin, pendimethalin followed by pinoxaden and metribuzin for *P. minor* control in wheat. These results revealed that ~ 80–83% of respondents were using clodinafop, sulfosulfuron and pinoxaden herbicides. About 10–13% of respondents were using ready mix herbicides viz. sulfosulfuron + metsulfuron, mesosulfuron + idosulfuron for the control of *P. minor*. The use of pre-emergence herbicides against *P. minor* infestation was less popular as only 2–4% of respondents were

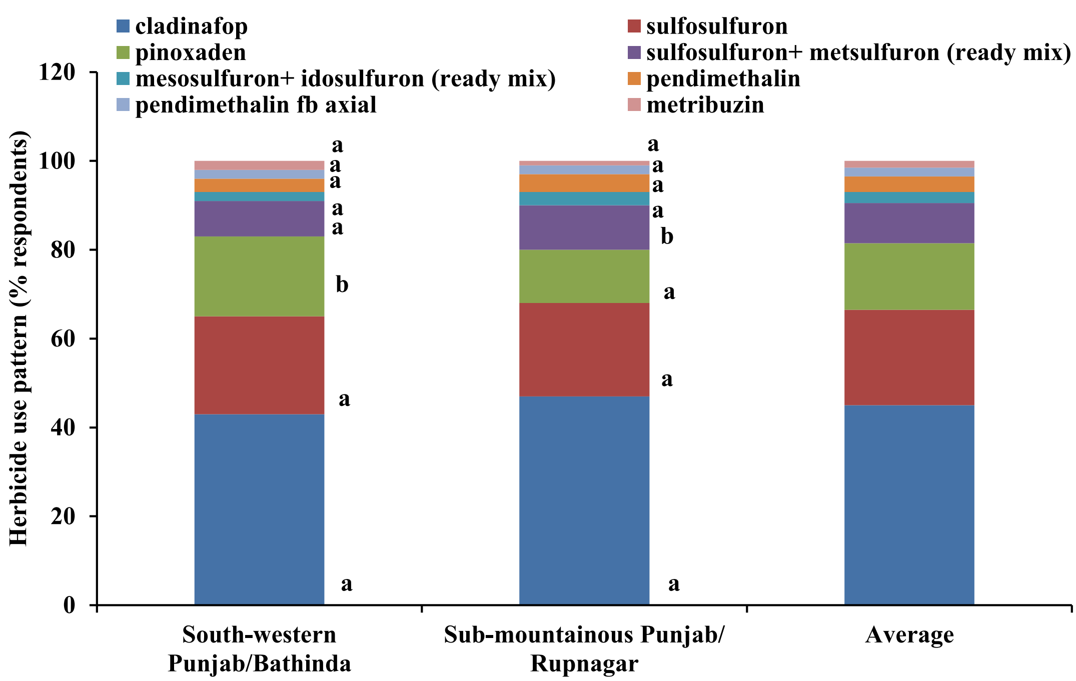

Fig. 2 Distribution of respondents based on herbicides used against *P. minor* control in wheat in Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. Mean values followed by same letters are statistically non-significant at $p < 0.05$ by Students' T-test

using pendimethalin as pre-emergence control measure. The use of pinoxaden was significantly ($p < 0.05$) higher in south-western Punjab, compared with the sub-mountainous region. Conversely, the use of sulfosulfuron + metsulfuron was significantly higher in sub-mountainous region. However, the use pattern of other herbicides against *P. minor* in wheat cultivation in two study regions was statistically non-significant.

On average, farmers were applying 1.87-times of ×-dose of total herbicides to control *P. minor* in wheat ecosystems. The highest herbicide use (2.65×) was observed in Bathinda block, whilst the lowest (1.25×) in Maur block of south-western Bathinda district (Table 3). We recorded ~ 70–82% control of *P. minor* in wheat established in two study regions, which was lowest in Talwandi Sabo block of south-western Punjab, while the highest in Anandpur Sahib block of Rupnagar district in sub-mountainous Punjab. Farmers perceived that clodinafop application has become ineffective against *P. minor* infestation in wheat. Conversely, sulfosulfuron and pinoxaden comprised ~ 21.5 and 15.0%, respectively of total herbicide use in Bathinda and Rupnagar districts (Fig. 1). Clodinafop was the most preferred herbicide against *P. minor* infestation in wheat because of its cheaper price and no phytotoxicity effect even when applied at higher doses with no residual effect on succeeding crops (Chhokar et al. 2018; Singh et al. 2021c). Additionally, clodinafop has much wider application window (Singh et al. 2021d). The extended application window of clodinafop offers farmers greater flexibility in timing their herbicide applications, thereby potentially enhancing the efficacy of weed control measures. This characteristic is particularly advantageous in agricultural settings where variable weather conditions or logistical constraints may necessitate a wider window of opportunity for herbicide application. By accommodating a broader range of application timings, clodinafop provides farmers with increased adaptability in managing weed infestations effectively throughout the growing season. Such flexibility is crucial for optimizing herbicide performance and maximizing weed control efficacy, ultimately contributing to improved crop yields and agricultural productivity.

Farmers wrongly believed that because the crop gets darkens following clodinafop application, it behaves as nitrogenous fertilizer (Soni et al. 2023; Singh et al. 2021d). Because of its cheap selling price, illustrious past and better compatibility with other herbicides, farmers frequently mix clodinafop with other herbicides (Singh et al. 2021d; Bhullar et al. 2014). This practice of mixing clodinafop with other herbicides offers several advantages and is commonly employed as a strategic approach in weed management strategies (Sekhar et al. 2024). Firstly, the cost-effectiveness of clodinafop makes it an attractive option for farmers seeking to optimize their herbicide investments while achieving effective weed control. Its affordability allows farmers to allocate their resources efficiently, thereby maximizing the economic returns on their herbicide purchases. Farmers also have priority of application of pinoxaden, because it works efficiently on *P. minor* that has become resistant to even higher doses of clodinafop and sulfosulfuron (Punia et al. 2017). However, the higher selling price of pinoxaden (~ 2.5-times higher than clodinafop and sulfosulfuron) was the major constraint for large-scale adoption in the study region. The price disparity presents a considerable economic constraint for farmers, particularly those operating within resource-constrained agricultural systems, where minimizing input costs is paramount for economic viability. As a result, the higher selling price of pinoxaden limits its accessibility and affordability for many farmers, thereby impeding its widespread adoption as a preferred herbicide choice for weed management in wheat cultivation. Consequently, despite its efficacy and potential benefits, the cost barrier associated with pinoxaden precludes its broader utilization in the study region, highlighting the importance of cost considerations in herbicide selection and adoption decisions by farmers.

These results revealed that ready-mix formulation of mesosulfuron + iodosulfuron provides reasonable control, but farmers showed reluctance of using it, because of appearance of toxicity symptoms particularly in wet field conditions or over-lapped/repeated spraying (Singh et al 2021c, 2021d). Such reluctance stems from concerns regarding the potential adverse effects associated with the application of the herbicide mixture, particularly in scenarios where environmental conditions may exacerbate its impact. The observed toxicity symptoms raise apprehensions among

Table 3 Herbicide use pattern and their efficacy against *P. minor* control in wheat in different administrative blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India

South-western Punjab/ Bathinda	×-dose	% control		Sub-mountainous Punjab/ Rupnagar	×-dose	% control	
		Recommended	×-dose			Recommended	×-dose
Maur	1.25	50–60	70–75	Ropar	2.25	50–55	70–80
Sangat	1.55	50–55	80–82	Chamkur Sahib	2.54	40–45	75–80
Bathinda	2.65	45–50	75–80	Anandpur Sahib	1.45	60–65	80–85
Talwandi Sabo	1.30	50–55	70–72	Morinda	1.98	50–55	75–80
Rampura	2.25	55–60	70–75	Nurpur Bedi	1.52	60–65	80–82

farmers regarding the safety and potential risks associated with the use of mesosulfuron + iodosulfuron, prompting them to opt for alternative herbicide options despite their potentially lower efficacy. This highlights the importance of considering not only the effectiveness of herbicides in weed management but also their safety profile and potential impact on crop health and environmental conditions. Addressing these concerns and ensuring proper stewardship practices are essential for promoting the wider acceptance and adoption of herbicide formulations such as mesosulfuron + iodosulfuron among farmers, thereby facilitating more sustainable weed management practices in agricultural systems.

These results revealed that farmers were using pre-emergence herbicide pendimethalin and metribuzin as post-tank mix with alternate herbicides (clodinafop, sulfosulfuron) to get desirable results (Fig. 1). Farmers using pendimethalin under optimum soil moisture conditions achieved highly satisfactory control against *P. minor*. However, it is concerning to note that some farmers are resorting to un-ethical practices, such as the application of metribuzin at the first irrigation by mixing it with urea fertilizer, despite its potentially deleterious effects. While this approach may offer acceptable control efficiency, it raises significant ethical and environmental concerns due to the potential risks associated with the indiscriminate use of herbicides in conjunction with fertilizers. As metribuzin is non-volatile, it leaches to groundwater. Once in groundwater, metribuzin is expected to persist due to its stability to hydrolysis and lack of light penetration. Such practices not only compromise the efficacy of weed management strategies but also pose risks to human health, crop integrity, and environmental sustainability. Therefore, it is imperative to promote responsible herbicide use practices among farmers, emphasizing the importance of adhering to recommended application guidelines and implementing integrated weed management approaches to mitigate the emergence of un-ethical practices and safeguard agricultural and environmental integrity. A similar practice of using isoproturon which is compounded due to resistance issues has become the major issue (Rasool et al. 2019; Soni et al. 2023). Moreover, the farmers who had taken land on lease are not aware of previous herbicide use history of the fields and tend to apply overdose of herbicides which exaggerates the problem (Singh et al. 2021d). We observed that Sangat block of Bathinda and Nurpur Bedi and Anandpur Sahib blocks of Rupnagar district had least herbicide resistance against *P. minor.* The lowest herbicidal resistance observed in these blocks was ascribed to the fact that farmers often rotate traditional rice–wheat cropping system with cotton/maize-wheat systems. It has been reported that herbicidal resistance against *P. minor* infestation in rice–wheat cropping system can be interrupted by introducing *Trifloium alexandranum*, *Avena sativa*, *Saccharum officinarum*and vegetables depending upon soil type and prevailing weather conditions of the region (Chhokar et al. 2012; Malik and Singh 1995). The success of this approach is contingent upon factors such as soil type and prevailing weather conditions of the region, highlighting the importance of tailoring crop rotation strategies to suit the specific agro-climatic characteristics of each locality. By diversifying cropping patterns and incorporating crops with different growth habits and susceptibility to herbicides, farmers can disrupt the life cycle of *P. minor* and reduce the selection pressure for herbicide resistance development. Therefore, promoting the adoption of diversified cropping systems and implementing tailored crop rotation strategies emerges as a promising approach to mitigate herbicide resistance and sustainably manage weed populations in agricultural landscapes.

Factors determining herbicide resistance against *Phalaris minor*

Logistic regression transforms the linear regression model using the logit function, which maps the probability of the outcome variable to the range of real numbers (Table 4). Logistic regression coefficients were used to interpret the direction as well as the magnitude of the relationship between the predictors and the log-odds of the outcome variable. Logistic regression helps provide necessary insights into how the predictor variables influence the probability of the binary outcome. Hosmer and Lemeshow test value (Chi-square 8.931, $df = 8$ and $p < 0.348$) was higher and null hypothesis was accepted, which indicates that the model adequately fits the data (Table 4). The Exp (β) coefficients representing the odds ratio, therefore, the role of individual factors in probabilities of occurring events (i.e. herbicide resistance) can be predicted. These results revealed higher Negelkerke r-square value which showed that dependent variable (herbicide resistance) explained ~ 64.4% variability contributed by 14 predictor variables in the data-set. This classification indicates that model predicts ~ 93.2% of cases correctly.

The Wald test enables estimation of coefficients for their statistical significance ($p < 0.05$). The model results illustrates that besides consistent herbicide use as a common factor, cultural factors e.g., sowing method (conventional/conservation; X_6), days taken to reach field capacity (X_7), time to first irrigation after sowing (X_8), crop rotation followed (X_9), and continuity of rice–wheat cropping system (X_{10}) determined the probabilities of herbicide resistance in *P. minor* in wheat cultivation. The 'β' coefficient values (X_9, Exp(β) = 0.754) revealed that if farmers follow crop rotation, there are ~ 75.4% chances of decreased herbicide resistance against *P. minor* infestation. Before the introduction of modern herbicides in the 1940s, crop rotation was a primary method of weed control (Vencill et al. 2012). Lathwal and Ahlawat (2011) also suggested crop rotation

Table 4 The description results of binary logistic regression model (enter method, first-run) developed for studying herbicide resistance against *P. minor* in wheat in different administrative blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. *Data pooled for two districts*

Model summary		-2 log likelihood		Cox & Snell R square		Nagelkerke R Square	
Step[1]		324.4[a]		0.484		0.644	
(Hosmer and Lemeshow test)							
	Chi square			Degree of freedom (*df*)		Sig.	
Step[1]	8.931			8		0.348[b]	
Observed				0.0	1.0	Percentage correct	
	Problem faced	0.0		91	34	86.7	
		1.0		18	107	97.1	
	Overall percentage					93.2	
Parameter		'β' Coefficient	Standard error (SE)	Wald value	Degree of freedom (*df*)	Significance	Exp(β)
Step 1[c]	X_1	1.065	0.592	3.235	1	0.572	2.900
	X_2	– 0.145	0.550	0.070	1	0.792	0.865
	X_3	0.404	0.615	0.431	1	0.512	0.668
	X_4	0.872	0.645	1.825	1	0.177	2.391
	X_5	0.790	0.847	0.871	1	0.351	2.204
	X_6	– 0.800	0.639	1.567	1	0.211	0.449
	X_7	– 1.442	0.579	6.207	1	0.013	0.236
	X_8	– 0.984	0.584	2.834	1	0.092	2.674
	X_9	– 0.282	0.911	0.096	1	0.057	0.754
	X_{10}	0.634	0.575	1.215	1	0.270	0.531
	X_{11}	– 0.036	0.873	0.002	1	0.967	0.965
	X_{12}	0.781	0.753	1.077	1	0.299	2.184
	X_{13}	– 0.659	1.132	0.340	1	0.560	0.517
	X_{14}	0.505	1.177	0.184	1	0.668	1.656

[a]The cut value is 0.500

[b]Estimation terminated at iteration number 4 because parameter estimates changed by less than 0.001

[c]Variable(s) entered on step-1: X_1–X_n

as one of the agronomic strategy for control of resistance in *P. minor* and reported higher grain yield of wheat grown on farmers' field without spraying any herbicides that adopted crop rotation. Any crop can be viewed in this sense as a filter that only allows specific weeds to get past its management practices (Booth and Swanton 2002). Crop rotation will change the selection pressures, preventing one weed from consistently succeeding snd establishing itself (Nichols et al. 2015). According to Franke et al. (2007), one year break from wheat production may almost exhaust the available seed bank as *P. minor* loses its ability to germinate. Alternative soil cultivation techniques, such as direct seeding or choosing crops other than rice can also affect *P. minor* pressure by altering the phyico-chemical properties of the soil and the seed dispersal in the soil profile (Singh et al. 2002).

These results revealed that only 10% farmers follow crop rotation, and 90% were continuously growing rice–wheat. Crop rotations provide an opportunity to incorporate diverse weed control practices into the farming system (Chhokar et al. 2008) and thus helps prevent the development of resistance (Vencill et al. 2012). Crop rotations allow for the strategic use of herbicides with diverse modes of action. By rotating herbicides with different mechanisms of action, farmers can prevent or delay the development of herbicide-resistant *P. minor* populations. This approach reduces the selective pressure exerted on the weed population, making it less likely for resistance to evolve and spread. Although, it is well known to the farmers that crop rotation is a critical factor for delay and/or management of herbicide resistance, yet there are situations where farmers do not have option for a change in existing crop rotation. For example, in south-western Punjab, although, both rice–wheat and cotton-wheat exists side-by-side, yet there are fields where they don't have assured underground water availability. In some situations, farmer's though have underground water available, but that water is of poor quality due to salinity and/or sodicity hazards and is therefore, not suitable for irrigation. Similarly, in sub-mountainous Punjab, maize-wheat farmers do not have adequate access to assured irrigation facility. There are situations where maize-wheat farmers are exclusively dependent upon rainfall for irrigation purpose. Therefore, crop rotation for reduced/delay in herbicide resistance is practically non-feasible.

These results elucidated that the fields which attain field capacity moisture regime within 10 days after sowing has 23.6% fewer chances of facing herbicide resistance (X_7, Exp(β)-0.236). Field capacity moisture regime represents the most appropriate moisture content of soils as *P. minor* flourishes extensively in the fertile and well moist soil which provides strength to *P. minor* to fight against the detrimental effect of post-emergence herbicides. Therefore, soil moisture should be maintained at optimum level which could favor wheat crop and not the weeds. Wheat can germinate from slightly drier zone whereas *P. minor* fails to germinate from dry soil (Chhokar et al. 1999). The farmers' who apply first irrigation within first 24 days after sowing have ~ 2.67-times higher chances of escaping the herbicide resistance, compared with those where first irrigation to crop is delayed (X_8, Exp(β) = 2.674). It could be ascribed to the fact that at three weeks after sowing of wheat, *P. minor* is at 2–3 leaf stage. Therefore, timely application of irrigation (24 days after sowing) allows the timely application of post-emergence herbicides. The delay in application of first irrigation results in delay of application of herbicides because it cannot be applied under dry soil moisture conditions. By this time, *P. minor* attains 4–5 leaves stage, and farmers developed an intention of using higher dose of herbicides to control those weeds, which aggravates the problem of herbicide resistance in *P. minor*.

Those farmers who opted for rice residue management technologies for wheat establishment, e.g., zero tillage, happy seeder and super seeder technology had ~ 65% lower chances of facing herbicide resistance against *P. minor* (X_6, Exp(β) = 0.449) as compared to the conventional methods of wheat sowing following open field rice residue burning. Zero tillage technology lowers the *P. minor* density as the soil is not disturbed, therefore reduces the weed infestation in fields and eventually the decreased herbicide spray and resistance. Conversely, in the fields sown with happy seeder technology with surface retention of rice residues exerts adverse impact on weed seed germination due to physical (reduction in light) and chemical changes (allelopathy) in the seed environment (Nichols et al. 2015; Bhatt et al. 2021). There was 14 and 52% (Mann et al. 2004) reduced germination of *P. minor* in fields with zero tillage method of wheat sowing compared to conventional method of wheat sowing. Reduced weed count in ZT might also be attributed to the presence of rice residues that interfered with weed emergence and growth by posing physical (light transmittance) or chemical (allelopathy) hindrance (Khaliq et al. 2013). Zero tillage technology for wheat establishment minimally disturbed weed seed bank, making it unable to come to upper layers of soil surface. Conversely, under the conventional method of wheat establishment, a fine seed bed is being prepared following intensified tillage due to multiple passes of ploughing machinery followed by line sowing of wheat with seed-cum-fertilizer drill. Therefore, intensive soil disturbance brings the *P. minor* seeds to the upper layers of soil surface and contribute towards higher germination and severe infestation. Zero tillage method of wheat establishment has created sizeable niche area in the rice–wheat cropping system in the study region (Singh et al. 2020). Therefore, there is a need to focus on zero tillage technology with crop residue retention as ecologically more sustainable and resource efficient technology.

These results revealed that intensive rice–wheat cropping system (> 10-years) has been problematic with ~ 53.1% chances of herbicide resistance against *P. minor* (X_{10}, Exp(β) = 0.531), compared with the fields where the continuity in rice–wheat cropping system was broken. High resistance (95%) against isoproturon herbicide use in intensive rice–wheat cropping system in Punjab (India), compared with the diversified cropping systems has also been reported earlier (Singh et al. 2021d). Over 90% of *P. minor* seeds fall to the ground prior to harvest, hence increasing the weed's seed bank in the crop field (Singh et al. 2013). According to studies, the *P. minor* seeds were more accumulated in the top 5.0 cm of the transplanted rice (Franke et al. 2007). The *P. minor* seeds can withstand anoxic conditions in rice fields, and deep placement of *P. minor* seeds during puddling operation further reduces the risk of seeds being exposed to high temperature (Chhokar et al. 2012). Crop management in rice supports the survival of *P. minor* in rice–wheat system. *Phalaris minor* seed is susceptible to solarization but puddling operation carried out in rice fields places the *P. minor* seed in deeper layers of soil thus avoiding its exposure to higher temperatures and hence survival of weed seed (Om et al. 2004). The inherent ability of *P. minor* seed in using NO_3 as an electron acceptor in electron transport system helps tolerate anoxia conditions (Singh et al. 1999; Parasher and Singh 1984). Reggiani et al. (1985) demonstrated that nitrate is used in the anaerobic germination of rice and it was subsequently suggested that rice coleoptiles play a part in nitrate's pH regulation (Kaiser and Brendlebehnisch 1995; Fan et al. 1997). The life of anoxic maize root tips appears to be prolonged by an enhanced nitrate supply (Roberts et al. 1985).

Overall, rice–wheat monoculture assist in increasing the *P. minor* seed bank by providing strong ecological support for the seed's ability to survive. The soil disturbing sowing techniques aid in the proper placement of *P. minor* seeds in the ecosystem where fine-textured soil provides the desired moisture for an adequate amount of time for their emergence. Crop rotation help re-establish diversity in weed flora in addition to delaying herbicide resistance by deployment of several management methods (Singh et al. 2021d). Growing *Trifloium alexandrinum* for two years may even be able to deplete the soil seed bank of *P. minor*, resulting in a long-term solution (Malik and Singh 1995). These are the innovative agronomic approaches involving development of environmentally friendly weed control that support crop production while weed populations are reduced through efficient use of agricultural inputs and resources. By combining different weed control techniques, such as preventive, physical, cultural and chemical ones that aid in preventing weed resistance, an integrated weed management approach would provide long-lasting weed control.

Several other socio-personal characteristics of the respondent farmers as well as herbicide application factors help to explain the data-set variability in the model, but they do not contribute significantly. It was discovered that people with smaller land holdings (up to 2 ha) and were younger age groups (up to 45 years) had less problem of *P. minor* infestation. Low *P. minor* density in the fields of small land holding was mainly ascribed to follow-up of crop rotation. Additionally, these farmers often perform cultural weed control measures, which contribute towards decreased chances of resistance against herbicides. On the other hand, farmers who had low education status and/or those who took land on lease had more chances to encounter herbicide resistance problems. These results revealed that most of the farmers knew about herbicide resistance, but despite that they did not follow herbicide rotation until they come to face this problem. They tend to use the same herbicide till it is giving favorable weed control efficiency in their fields. Continued use of the same molecule (group/brand/mode of action) can speed up the development of resistance by imposing selection pressure (Bhullar et al. 2014).

Effect of spray technique on herbicide use efficiency

Effective weed control depends not only on proper selection of herbicides, weed flora, optimum herbicide dose and timely application of herbicides, efficient spray technique has significant impact on herbicide use efficiency in terms of control on weed infestation (Norsworthy et al. 2012; Butts et al. 2018. These results revealed that ~ 89.2% farmers used flood jet and hollow cone nozzles, and only 10.8% farmers used flat fan nozzle (recommended one) for herbicide spray (Table 2). The most appropriate nozzle for herbicide application is the flat fan nozzle due to its swath and entire weed foliage coverage in the swath limit (Qasem 2011). The flood jet nozzle is considered appropriate for spraying pre-emergence herbicides, while hollow cone nozzle is designed for the application of fungicide and insecticide application (Miller and Bellinder 2001). The farmers of the study region do not prefer flat fan nozzle because of convenience of using other nozzles for pesticides application.

Besides, volume of water used for herbicide spray has significant effect on efficient weed control. These results revealed that only 4.4% farmers were using recommended water volume (500 L ha^{-1}) for the application of post-emergence herbicides, while ~ 90% farmers under-used water volume (225–300 L ha^{-1}) for the application of herbicides (Table 2). About 55.9 and 34.1% of the respondent farmers in the studied regions were using 300 and 225 L ha^{-1}, respectively for the application of herbicides. The reduced use of volume of water for herbicide application was ascribed to the high labor costs. Since, the volume of water used for herbicide application has significant impact on area coverage, surface contact and subsequent penetration and translocation of the herbicide within *P. minor* plants, therefore, volume of water use for the application of herbicides has considerable contribution towards efficient weed control (Creech et al. 2017; Norsworthy et al. 2012). Use of adequate volume of water ensures thorough coverage of the target weed, including foliage, stems, and other plant parts and allows satisfactory translocation of herbicide to reach the site of action effectively, thereby reducing the chances of herbicide resistant biotypes surviving due to insufficient herbicide movement. The reduced volume of water for herbicide application was ascribed to the misleading conceptions among farmers that concentrated sprays provide good results and higher water volume dilutes the herbicide and therefore, efficiency is reduced (Singh et al. 2021d; Punia et al. 2013). With this mindset, farmers tend to use even more concentrated sprays to deal with the consistently increasing herbicide resistance (Singh et al. 2021d). Insufficient water volume often results in over/under dosing of the herbicide, affecting its efficacy and potentially promoting herbicide resistance development. Proper dilution, achieved through appropriate water volumes, allows for optimal herbicide performance and reduces the likelihood of resistance (Punia et al. 2013; Yadav et al. 2006).

A large majority of farmers (~ 51.3 and 55.0%, respectively at Bathinda and Rupnagar districts) preferred herbicide application at 40–45 days after sowing (Table 5). Conversely, only few farmers (~ 4.7 and 7.0%, respectively in Bathinda and Rupnagar districts) sprayed their crop with herbicide at the recommended time (30–35 days after sowing) (Table 5). We identified two major reasons behind the delayed herbicide application as (i) delayed first irrigation, and (ii) delayed appearance of field capacity moisture regime due to decreased temperature. Besides, farmers also had misconception that application of herbicide at later stages (at 4–5 leaf stage of *P. minor*) gave better

Table 5 Distribution of respondents based on application of pre-and post-emergence application of herbicides depending upon growth stage of *P. minor* growth stage in Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India

Time of spray	*P. minor* growth stage	Study region			
		South-western Punjab/Bathinda		Sub-mountainous Punjab/ Rupnagar	
		First spray	Second spray	First spray	Second spray
0 DAS	No germination	9 (6.0%)	–	4 (4.0%)	–
20–25 DAS	25–30% germination	15 (10.0%)	–	9 (9.0%)	–
25–30 DAS	> 50% germination (1–2 leaf stage)	4 (2.7%)	–	5 (5.0%)	–
30–35 DAS	2–3 leaf stage	7 (4.7%)	–	7 (7.0%)	–
35–40 DAS	2–4 leaf stage	15 (10%)	2 (1.3%)	10 (10.0%)	3 (3.0%)
40–45 DAS	3–4 leaf stage	77 (51.3%)	7 (4.7%)	55 (55.0%)	3 (3.0%)
45–50 DAS	4–5 leaf stage	13 (8.7%)	10 (6.7%)	6 (6.0%)	5 (5.0%)
> 50 DAS	> 5 leaf stage	10 (6.7%)	107 (71.3%)	4 (4.0%)	77 (77.0%)

control. Therefore, they prefer herbicide application at later stage with perception that it will cover all the emerged weeds, and rarely bother for a critical period (leaf stage). At later stages, weeds easily resist the recommended dose, therefore, farmer's inadvertently sub-labeled the herbicide dose and give chances to acquire resistance against those herbicides. These factors often lead to inadequate coverage and reduced efficacy of herbicides (Qasem 2011; Soni et al. 2023; Kaur et al. 2019). Balyan et al. (1988) reported efficient weed control when herbicides were applied up to 35 days after sowing, and poor control under delayed application situations. Weeds receive under/over-dose, which leads to the speedy development of resistance (Punia et al. 2013). Therefore, due to lack of adequate knowledge regarding role of efficient spray techniques in weed control, farmers arbitrarily increased the herbicide dose to overcome the effect of poor control, which eventually imposes selection pressure and contributing to resistance (Soni et al. 2023; Chhokar et al. 2008).

Farmers' perception regarding poor efficacy of herbicides

Henery Garrett's (1969) rank technique was used to rank the reasons responsible for poor efficacy of herbicides. Perception analysis bifurcated respondents of the study regions among two groups (Table 6). About 75.6% respondents reported that the prime cause of poor efficacy of herbicides was the poor quality of herbicides. Farmers keep on changing the brand of herbicide but of same molecule available in the local market. Additionally, several farmers believe that although there was no issue of quality of herbicides, yet they are not getting desired results. These results therefore, indicate the existence of herbicide resistance in wheat against *P. minor.* About 25.2% of farmers in this group said that the persistence of monoculture, the use of inadequate or excessive amounts of herbicides, and the difficulties of monitoring herbicide usage under the leasing system contributed to the development of resistance populations. They discovered that *P. minor* regeneration is supported by increased urea usage. The increased nutrient content increases *P. minor's* capacity to compete against wheat.

The type and density of the above-ground weed flora in the agricultural fields was largely influenced by the soil weed seed bank, which is a primary source of weeds. Farmers gave 2nd rank to the seed bank from previous year's crop harvest for poor control of *P. minor*. The seed bank consists of both fresh seeds that the plant has just shed and older seeds that have been in the soil for a long time (Norris 2007; Skuodien et al. 2013). According to estimates, only around 10% of the viable weed seeds produced in a given season germinate and grow into seedlings, while the remaining seeds germinate in subsequent years depending on the seed position (Swanton et al. 2000). According to reports, the largest seed reserve is found in the top 0–5 cm of the soil and declines as soil depth increases (Chauhan et al. 2006; Mishra and Singh 2012). Weed species concentrations and weed seed banks are strongly influenced by soil disturbance, crop rotations, and crop management techniques (Grundy et al. 2003; Koocheki et al. 2009; Hosseini et al. 2014; Chen et al. 2017; Weisberger et al. 2019). Improper herbicide dose (under dose during initial years and intermittent overdose), delayed herbicide application (when fields reach field capacity moisture regime following after first irrigation) and faulty spray techniques (viz. low water volume, improper nozzle, use of power sprayer, and uneven spray etc.) were given 5, 6 and 7th rank, respectively.

Table 6 Ranking of factors affecting farmers' perception on causes responsible for poor efficacy of herbicides against *P. minor* control in wheat in different administrative blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. *Data pooled for two districts*

Particular	Number of respondents ($n = 250$)							Total score	Mean score	Rank
	1	2	3	4	5	6	7			
Poor quality of herbicides	55 (22)†	65 (26)	69 (27.6)	39 (15.6)	14 (5.6)	8 (3.2)	0 (0)	15,337	61.4	1
Everything fine but now not getting good results	63 (25.2)	26 (10.4)	47 (18.8)	42 (16.8)	38 (15.2)	22 (8.8)	12 (4.8)	14,055	56.2	3
Faulty spray practices	1 (0.4)	2 (0.8)	2 (0.8)	16 (6.4)	40 (16)	67 (26.8)	122 (48.8)	7806	31.2	7
Late application	2 (0.8)	8 (3.2)	3 (1.2)	14 (5.6)	57 (22.8)	95 (38.0)	71 (28.4)	8798	35.2	6
Improper dose	48 (19.2)	51 (20.4)	28 (11.2)	31 (12.4)	34 (13.6)	20 (8.0)	38 (15.2)	13,234	52.9	5
Soil type	55 (22)	39 (15.6)	30 (12)	45 (18)	40 (16)	33 (13.2)	8 (3.2)	13,842	55.4	4
Seed bank from previous year's crop harvest	24 (9.6)	59 (23.6)	70 (28)	63 (25.2)	27 (10.8)	5 (2.0)	2 (0.8)	14,281	57.1	2

†Values in parentheses represent the % of respondents

Economic and production efficiency

We appraised economic evaluation based on ACCIs, AGRs, ANRs and the B-C ratio of wheat production in the study regions (Table 7). The ACCIs varied between 339.1 and 432.8 US\$ ha^{-1} in different blocks of Bathinda district in south-western Punjab, while between 343.1 and 386.9 US\$ ha^{-1} in blocks of Rupnagar district in sub-mountainous Punjab. The ACCIs was significantly ($p < 0.05$) lowest in Maur and Talwandi Sabo blocks, and the highest in Bathinda block, while other blocks of south-western Punjab fell in-between. Similarly, Anandpur Sahib block has significantly lower ACCIs, while Ropar block of sub-mountainous Punjab has the highest ACCIs for wheat production. These differences in ACCIs were ascribed to the differences in herbicide use pattern and × -dose of applied herbicides in these blocks. These results revealed significantly lower AGRs for Rampura, while the highest AGRs were observed for Bathinda block of south-western Punjab. In sub-mountainous Punjab, significantly higher AGRs were recorded for Anandpur Sahib, while the lowest for Nurpur Bedi block. These differences in AGRs for studied blocks of two regions were ascribed to the yield differences (Fig. 3). With the highest ANRs of 1014.8 US\$ ha^{-1} in Maur block of south-western Punjab and 1042.2 US\$ ha^{-1} for Anandpur Sahib, wheat production in these blocks was economically more efficient with significantly highest B-C ratio. The economic efficiency of 9.17 US\$ ha^{-1} d^{-1} for Bathinda block was significantly higher, while value of 8.78 US\$ ha^{-1} d^{-1} was the lowest for Rampura block in south-western Punjab (Fig. 4). However, there was a non-significant difference in economic efficiency of wheat production in different blocks of sub-mountainous Punjab. Figure 5 illustrates significant differences in the production efficiency of wheat in different blocks of south-western Punjab. The production efficiency was significantly higher for Bathinda and Maur blocks (which themselves were *at par*), while the lowest for Rampura block of south-western Punjab.

Conclusions

These results highlights the widespread prevalence of herbicide resistance against *P. minor* in wheat ecosystems exacerbated by suboptimal herbicide application practices and cultural factors. Addressing this challenge requires a holistic approach that emphasizes the adoption of integrated weed management strategies, including crop rotation and timely irrigation, to mitigate herbicide resistance and ensure sustainable agricultural practices. Cultural practices (like mono-cropping of rice–wheat system, conventional sowing method of wheat, delay in first irrigation, and excessive use of nitrogenous fertilizers etc.) has made *P. minor* flourish

Table 7 Economic indices used for evaluating the monitory returns to the respondents using variable rates of herbicide application for the control of *P. minor* infestation in wheat in different administrative blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India

South-western Punjab/ Bathinda	Average cost of cash inputs (ACCIs) (US\$ ha^{-1})	Average gross returns (AGRs) (US\$ ha^{-1})	Average net returns (ANRs) (US\$ ha^{-1})	Benefit–cost ratio (B-C ratio)	Sub-mountainous Punjab/ Rupnagar	ACCIs (US\$ ha^{-1})	AGRs (US\$ ha^{-1})	ANRs (US\$ ha^{-1})	B-C ratio
Maur	339.1^{a}	1353.8^{c}	1014.8^{d}	3.99^{e}	Ropar	379.7^{D}	1379.0^{C}	999.3^{B}	3.63^{B}
Sangat	371.6^{b}	1334.9^{b}	963.4^{b}	3.59^{c}	Chamkaur Sahib	386.9^{E}	1372.7^{B}	985.8^{A}	3.55^{A}
Bathinda	432.8^{d}	1360.1^{d}	927.3^{a}	3.14^{a}	Anandpur Sahib	343.1^{A}	1385.3^{D}	1042.2^{D}	4.04^{E}
Talwandi Sabo	341.9^{a}	1341.2^{b}	999.4^{c}	3.92^{d}	Morinda	354.7^{B}	1372.7^{B}	1018.0^{C}	3.87^{D}
Rampura	390.3^{c}	1312.9^{a}	922.6^{a}	3.36^{b}	Nurpur Bedi	367.2^{C}	1369.6^{A}	1002.4^{B}	3.73^{C}
Mean	375.1	1340.6	965.5	3.57	Mean	366.3	1375.9	1009.6	3.76

Mean values followed by same letters are statistically non-significant at $p<0.05$ by Least Significant Difference (LSD) test. Lower case values were used to differential blocks of Bathinda, while the upper case letters differentiate blocks of Rupnagar district

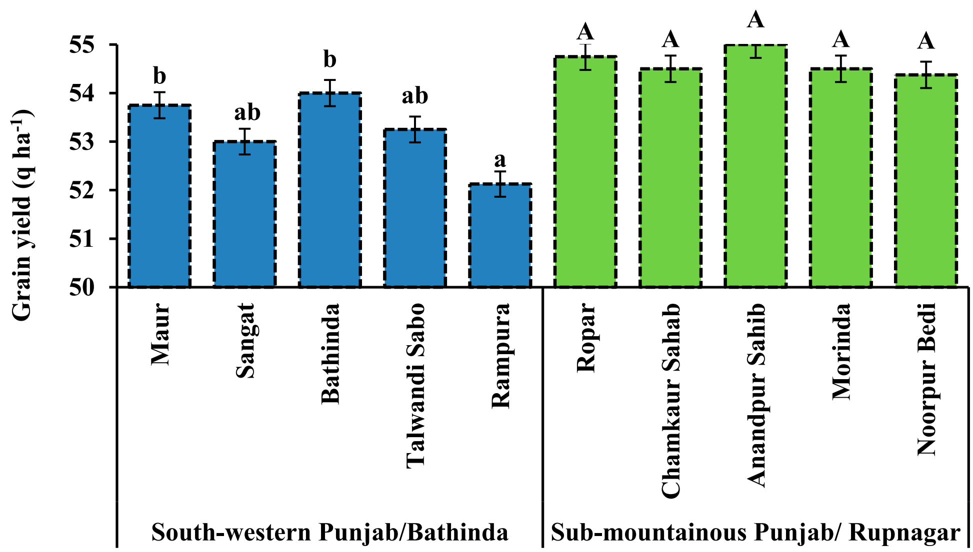

Fig. 3 Mean wheat grain yield (q ha^{-1}) at different farmers' fields in different blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. Error bars indicate standard error from mean. Mean values followed by same letters are statistically non-significant at $p<0.05$ by Least Significant Difference (LSD) test. Lower case values were used to differentiate blocks of Bathinda, while the upper case letters differentiate blocks of Rupnagar district

in wheat fields of north–western India. Initial high density of *P. minor* is later exposed to improper spray techniques (delay in time of spray, lower water volume and improper nozzles), raised the probabilities of occurrence of resistance by imposing selection pressure. Further, use of overdose of herbicides with repetition of same mode of action year after year has exaggerated the problem of herbicide resistance. Therefore, it is important to encourage farmers to use good agricultural practices that include crop rotation and conservation methods of sowing (zero tillage). Large scale demonstrations of improved herbicide spraying techniques for farmers and pesticide dealers are also required. Farmers should be instructed on right amount of herbicides, preferably with a varied mode of action in a cyclic fashion. Policies that promote crop diversification (such as replacing rice with maize during *kharif* season alongwith subsidy on drip irrigation), zero tillage with residue retention, and the gradual phasing out of fraudulent and inefficient herbicides from the market are required.

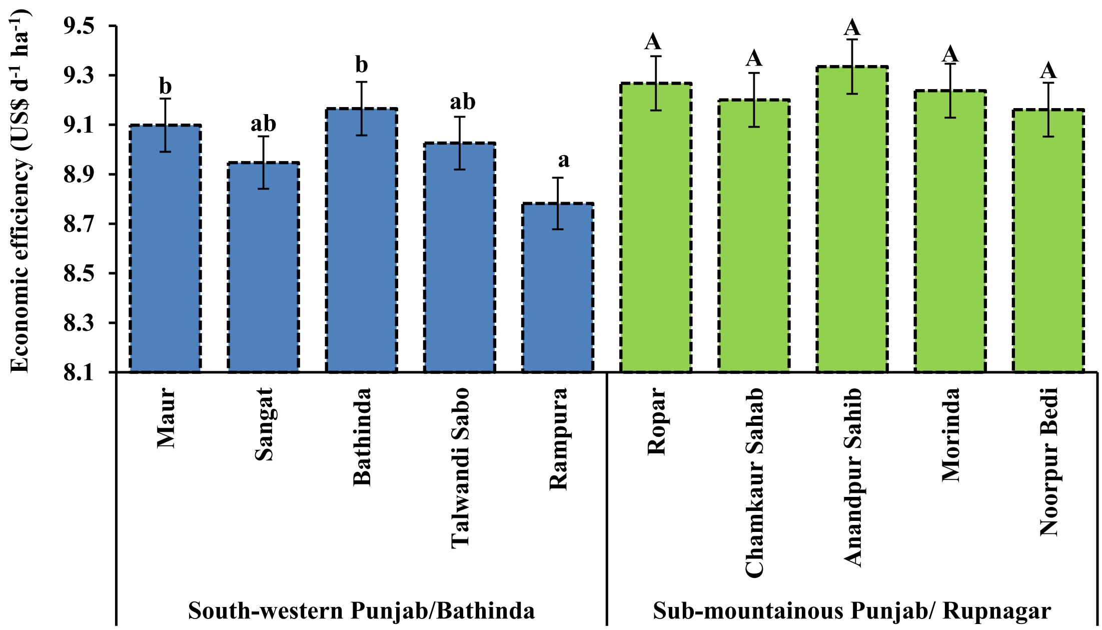

Fig. 4 Mean economic efficiency of wheat at farmers' fields in different blocks of Bathinda (south-western region) and Rupnagar (sub-mountainous region), Punjab in north–western India. Error bars indicate standard error from mean. Mean values followed by same letters are statistically non-significant at $p < 0.05$ by Least Significant Difference (LSD) test. Lower case values were used to differentiate blocks of Bathinda, while the upper case letters differentiate blocks of Rupnagar district

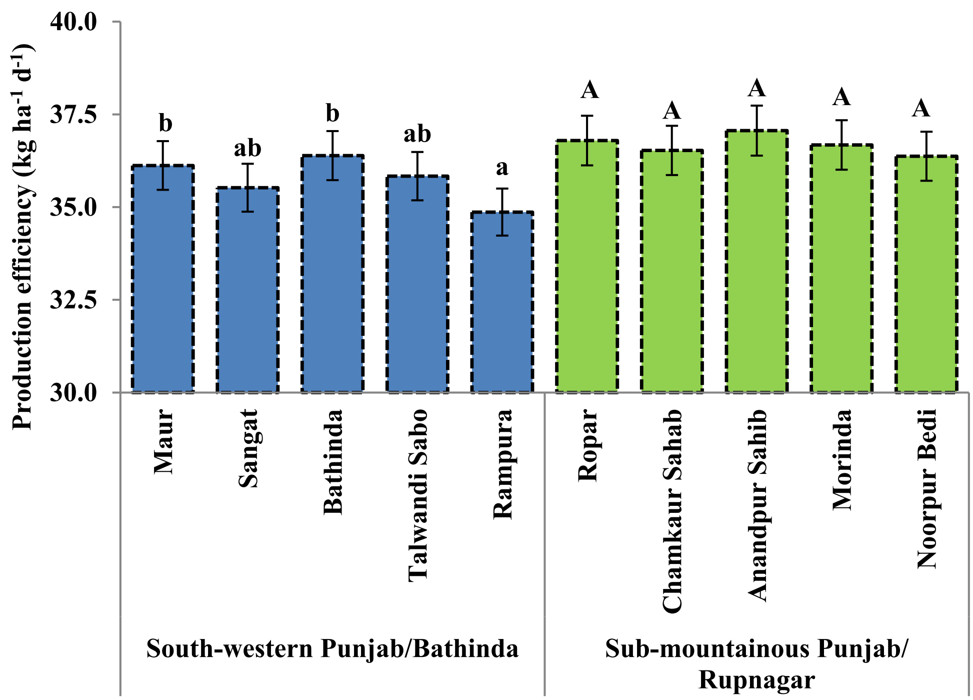

Fig. 5 Mean production efficiency of wheat at farmers' fields in different blocks of Bathinda (south-western region) and Rupnagar (sub-montainous region), Punjab in north–western India. Error bars indicate standard error from mean. Mean values followed by same letters are statistically non-significant at $p < 0.05$ by Least Significant Difference (LSD) test. Lower case values were used to differentiate blocks of Bathinda, while the upper case letters differentiate blocks of Rupnagar district

Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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