

Wheat production functions under irrigated saline environment and foliar potassium fertigation

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A field experiment was conducted for two consecutive years to develop management alternatives for wheat cultivars (salt-tolerant and salt non-tolerant) cultivated under irrigated saline environment (groundwater, 4, 8 and 12 dS m⁻¹) and foliar potassium fertigation. The grain yield of wheat cultivars decreased with the increase in salinity levels of irrigation water. The foliar potassium fertigation during the heading stage of wheat cultivars ameliorated the adverse effect of salinity and resulted in the increase in grain yield. In this study, empirical equations for wheat yield known as production function have been developed. The production functions were developed keeping grain yield parameter as output, besides the many input parameters pertaining to quantity and quality of the irrigation water, quantity of potassium applied as foliar spray and rainfall depth during the crop growth period. The production function with higher coefficient of determination (R^2) may be used to predict grain yield of both salt-tolerant and salt non-tolerant cultivars under different saline irrigation regimes, rainfall and irrigation water depths, besides the dose of potassium sulphate (K₂SO₄) for foliar spray. The production function which gave the highest R^2 value (i.e. 0.82 for KRL-1-4 and 0.97 for HD 2894 wheat cultivars) could be used for foliar spray under different salinity regimes with high expectation of grain yield. The predicted grain yield and estimated quantity of potassium under different salinity levels of irrigation water may prove useful to different stakeholders for enhancing the wheat yield in high saline water areas. The stakeholders can predict the grain yield under similar circumstances as explained in this experiment and estimate the appropriate potassium doses to be applied for enhancing the wheat yield.

Keywords: Foliar potassium fertigation, irrigation water, production function, salt-tolerant cultivar, wheat yield.

WHEAT (*Triticum aestivum*, L.) is one of the major cereal crops cultivated all over the world to meet the demand of the global population. Wheat per se provides

almost 20% calories to its consumers world over¹. The total wheat production in India during 2015–16 was 92 million tonnes (mt). Rapid increase in wheat consumption due to high population growth is projected to surpass the domestic production in future. Out of 328.7 million hectares (m ha) geographical area of India, about 120.4 m ha (37%) is affected by various kinds of land degradation². This poses a threat to the food security of the burgeoning population. Therefore, it is imperative to increase the production with the limited available resources and other challenges so as to feed the entire population.

One of the major reasons for decrease in crop yield is the degradation of irrigation water quality due to improper agricultural water management practices and overexploitation of available water resources. The soil and groundwater salinity poses a threat to irrigated agriculture in many parts of the world. Nearly 20% of the world's cultivated area and about half of the world's irrigated lands are affected by salinity³. Excess amount of salt in the soil root zone adversely affects the growth and development of plants.

The growth and yield of wheat under irrigated conditions is affected by soil–water–plant–atmospheric parameters of the region. The development of salt-tolerant cultivars is widely recognized as an effective way to overcome the limitations of crop production under saline environment⁴. The foliar application of nutrients on the crop is being widely accepted nowadays. Many researchers have shown the direct benefits of applying nutrients in the form of foliar on the crops in terms of increase in their growth and yield. The supply of water and nutrients to the crops in saline irrigation environment is restricted, which affects their growth and yield with low water productivity. It is desirable to obtain high grain yield with lesser amount of water so as to save the resources. Therefore, field experiments assist in generation of primary data to study the effects of these parameters on yield of wheat crop. Potassium nitrite (KNO₃) and potassium chloride (KCl) found to be equally effective in increasing the wheat yield⁵. The beneficial effects of KNO₃ application were observed on perennial ryegrass grown in saline conditions⁶. Pot experiment was conducted to determine

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Table 1. Physical and chemical properties of soil of the experimental field

Properties	Soil depth (cm)				
	0–15	15–30	30–45	45–60	60–90
Physical properties					
Soil texture	Sandy loam	Sandy loam	Loam	Loam	Clay loam
Sand (%)	52.4	53.7	44	39	38
Silt (%)	21	19	23	25	27
Clay (%)	26.6	27.3	33	36	34
FC (w/w)	22	25.6	27.9	32.8	33
PWP (w/w)	9.5	10.2	13.7	14.7	15
Bd (g cm ⁻³)	1.41	1.43	1.49	1.47	1.56
K_{sat} (mm/day)	274	262	186	191	195
Chemical properties					
EC (dS m ⁻¹)	0.20	0.28	0.36	0.40	0.45
pH	7.90	8.50	8.31	8.42	8.57
Organic matter (%)	0.50	0.48	0.46	0.41	0.37
N (ppm)	179	159	130	123	126
P (ppm)	3.3	3.7	129.6	4.3	4.1
K (ppm)	172.4	177.7	182.5	188.1	191.2

FC, Field capacity; PWP, Permanent wilting point; Bd, Bulk density; K_{sat} , Saturated hydraulic conductivity and EC, Electric conductivity.

the effect of potassium on wheat under saline and non-saline conditions, and it found that foliar application of K^+ ameliorated the effect of salinity⁷. Therefore, it is essential to predict wheat yield under the adverse effect of salinity and using techniques like foliar application of potassium. The concentration of potassium to be applied as foliar on wheat crop varies according to the salinity levels. The increase in KNO_3 concentration in the saline nutrient solution proved to be effective in increasing K^+/Na^+ ratio in shoot and root of winter wheat⁸.

The estimation of crop yield under irrigated saline environment is essential in the development of management alternatives. Prediction of grain yield under irrigated saline environment with the amount of potassium to be applied as foliar for better growth is important. The wheat yield was directly influenced by quality and quantity of irrigation water and initial soil salinity⁹. Crop–water–salinity production function coupled with a soil–water–salinity dynamic model to maximize net return of wheat crop per unit of irrigated area has been developed¹⁰. The studies have increased on determining efficiency level of inputs using production functions that are used in agricultural activities in terms of agricultural production¹¹. The development of production functions requires experiment-generated database to develop empirical models. Therefore, it is necessary to develop appropriate packages and practices of raising the crops under suitable water management technologies for enhancing productivity in irrigated saline environment to feed the ever-increasing population.

In view of the above, an experiment was undertaken on two wheat cultivars (i.e. a salt-tolerant cultivar KRL-1-4 and a salt non-tolerant cultivar HD-2894) to develop production functions for wheat yield under irrigated saline

environment and foliar potassium fertigation with better prediction accuracy.

Materials and methods

Study area

The experiment was undertaken in the research farm of Water Technology Centre (WTC), ICAR-Indian Agricultural Research Institute (IARI), New Delhi. The experiment was conducted for two years during the *rabi* season of 2011–12 and 2012–13. WTC research farm is situated between 77°09'36"E long. and 28°37'55"N lat. at an average elevation of 230 m above mean sea level. The experimental farm is equipped with surface irrigation facility with an overhead tank to store and prepare artificial saline water of different salinity levels for subsequent irrigation to different experimental plots. Table 1 shows the physical and chemical properties of the soil of the experimental field.

Climate details

The climate of New Delhi, India is semi-arid and subtropical with hot and dry summers and cold winters. The climate of this area falls under the agro-climate zone of 'Trans-Gangetic Plains'. The temperature during summer months (i.e. May and June) is maximum and varies from 40°C to 46°C. The temperature during winter months reaches its lowest during January with the minimum ranging between 3°C and 7°C, and occasionally reaching below 0°C. Average annual rainfall of Delhi is about 750 mm and 80% of this occurs during three active

southwest monsoon months, viz. July, August and September.

Field experiment

Field experiment was laid out in split-split plot design with four main plots and three replications. The four main plots were irrigated with one control and three different salinity levels (i.e. S_1 (1.7 dS m^{-1} , groundwater salinity; control): S_2 (4 dS m^{-1}): S_3 (8 dS m^{-1}) and S_4 (12 dS m^{-1})). Each main plot was further divided into two sub-plots for foliar potassium (F_1) and non-foliar potassium (F_0) treatments on both wheat cultivars. Further, each sub-plot was divided into two sub-sub-plots to accommodate two different wheat cultivars, viz. salt-tolerant cultivar V_1 (KRL-1-4) and salt non-tolerant cultivar V_2 (HD 2894). The size of the main plot was $9 \text{ m} \times 5 \text{ m}$ and the spacing between the two main plots was 3 m. The spacing between the two sub-plots was 1.5 m within the main plot. The wheat cultivars were sown with row-to-row spacing of 20 cm during experimental years of *rabi* 2011–12 and 2012–13 respectively. Figure 1 presents a field view of the experiment.

Wheat cultivars grown in the experiment

Two different wheat cultivars, viz. the salt-tolerant cultivar KRL-1-4 developed by ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana and a salt non-tolerant cultivar HD 2894 developed by ICAR-IARI, New Delhi were selected for the experiment. The purpose of such selection was to study the effect of foliar potassium fertigation on grain yield of both salt-tolerant and non-tolerant cultivars under irrigated saline environment, and to subsequently develop management alternatives for increasing the yield under saline regimes.

(i) *KRL-1-4 variety (V_1)*: This is the first salt-tolerant wheat variety released in 1990 by ICAR-CSSRI. This is suitable for the northwestern agro-climatic conditions of India. This variety is a dwarf variety and maturity period varies from 130 to 137 days with an average plant height of

87 cm. The potential yield is 5 tonne ha^{-1} at a salinity level of 7 dS m^{-1} and percentage of protein in grain is about 12.

(ii) *HD 2894 variety (V_2)*: This is a hybrid wheat variety released by ICAR-IARI. It is suitable for the northern Indian agro-climatic conditions prevailing in the North West Plain Zone (NWPZ) of India. This is a medium dwarf variety and maturity period varies from 118 to 146 days with an average plant height of 90 cm. The potential yield is $5.2 \text{ tonne ha}^{-1}$ and percentage of protein is about 11.

Foliar application of potassium

Potassium sulphate fertilizer (K_2SO_4) was used for foliar potassium fertigation during both years of experiment. Foliar potassium in the ratio of $\text{K}^+ : \text{Na}^+$ (1 : 10) was applied during the heading stage of the crop for three consecutive days during *rabi* 2011–12 and 2012–13 cropping seasons. The quantity of foliar potassium fertigation applied was estimated based on $\text{K}^+ : \text{Na}^+$ (1 : 10) ratio¹², and the quantity of Na^+ supplied to different plots based on different levels of irrigation water salinity to be maintained and its quantity. The measured amount of potassium sulphate was diluted to 1% level and then applied through manual spraying using a knapsack sprayer. The quantification of potassium sulphate fertilizer was done based on the applied Na^+ under different irrigation regimes. Figure 2 presents a field view of wheat leaves just after foliar application.

Production functions of wheat cultivars

Production functions have been developed for wheat cultivars under irrigated saline environment and foliar potassium fertigation. The grain yield as output parameter besides the input parameters pertaining to quantity and quality of irrigation water, quantity of potassium applied as foliar spray and rainfall depths during the crop growth period were used for the development of production functions. Subsequently, the developed production functions can be used as alternative management scenarios with



Figure 1. Field view of the experiment on wheat cultivars (*rabi* 2012–13).



Figure 2. Field view of wheat leaves just after foliar application.

grain yield information of the two cultivars under study for a wide range of salinity regimes, effective rainfall and irrigation depths besides foliar potassium fertigation doses. The empirical relationships between grain yield and other easily quantifiable input parameters were used for development of production functions, as follows

$$G_Y = f(S_i, D_i, D_r, K_{fa}),$$

where G_Y is the grain yield of wheat per unit of area (tonne ha⁻¹), S_i the salinity of irrigation water (dS m⁻¹), D_i the depth of irrigation water applied to the crop (cm), D_r the rainfall depth during the period (cm) and K_{fa} is the quantity of potassium sulphate fertilizer applied during the heading stage through foliar application (kg ha⁻¹).

The parameters used in the development of empirical production functions are primarily governed by their measurement units and the range of data used for model development. Therefore, units of different parameters and range of data were mentioned for the developed production functions to assist the users. In order to increase the data points, the data acquired from field experiment and predicted by validated AquaCrop model¹³ for the same experiment were clubbed together to increase the predictive range and prediction ability of the developed production functions. The validated crop model is useful for simulating the range of conditions and provides the means to estimate production functions when experimental field data are not available¹⁴.

Results and discussion

Foliar potassium fertigation on wheat cultivars

The KRL-1-4 and HD 2894 cultivars under foliar treatment resulted in increase in grain yield by 6.5–22% and 3–15% respectively, compared to the non-foliar treatments with irrigation water salinity ranging from 1.7 to 12 dS m⁻¹ during *rabi* 2011–12. The foliar potassium fertigation resulted in enhancing the grain yield of KRL-1-4 cultivar by 4.5–20% compared to the control under all salinity levels.

For the HD 2894 cultivar, the increased yield due to foliar potassium fertigation varied from 2% to 14% compared to the non-foliar treatment. The trend of increase in grain yield for *rabi* 2012–13 was in line with that of *rabi* 2011–12 (Figures 3 and 4). The foliar potassium fertigation protocol to increase the productivity of wheat cultivars under irrigated saline environment was standardized using the experimental generated data¹⁵.

In order to understand the science behind the effect of foliar potassium application on plant physiological aspects, the pertinent literature on these aspects was reviewed. This showed that the epidermal surface of plant leaves bears a great number of pores called stomata. The

stomata are microscopic in nature and are bordered by two specialized epidermal cells called ‘guard cells’, which control the opening and closing of the stomata. Accumulation of potassium (K⁺) on the plant surface after foliar spray triggers an active exchange process in which protons are pumped out of the guard cells into the accessory cells. The change in water potential that results from such osmotic variations causes water to move in or out of the guard cells. When water potential of the guard cells becomes more negative than that of the surrounding cells, water enters into the guard cells by osmosis, which increases the turgor pressure¹⁶. Therefore, application of K⁺ plays a significant role in maintaining the turgor pressure due to which the stomatal opening is maintained under salinity stress for better photosynthesis, and thereby would lead to better plant growth and yield. The effect of potassium application in stimulating the biological process in plants leading to enhanced grain yield is also corroborated by many researchers^{17,18}. The foliar application of potassium is favourable and acts as an activator of several enzymes involved in carbohydrate metabolism and on the metabolism of nucleic acids, proteins, vitamins and growth substances¹⁹. The exogenous application of K under drought stress during critical growth stages enhanced stress tolerance of wheat by reducing toxic nutrient uptake and improving the physiological efficiency²⁰.

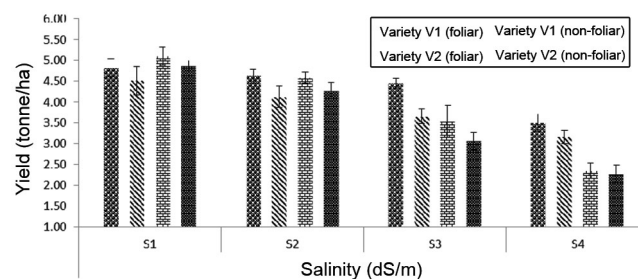


Figure 3. Grain yield of wheat cultivars with and without foliar potassium fertilization under irrigated saline regimes during *rabi* 2011–12. (Note: Error bars represent the standard error of observed data in all three replications.)

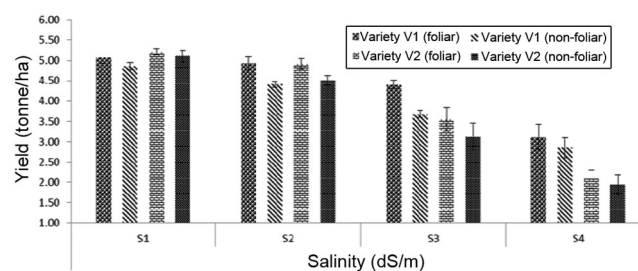


Figure 4. Grain yield of wheat cultivars with and without foliar potassium fertilization under irrigated saline regimes during *rabi* 2012–13. (Note: Error bars represent the standard error of observed data in all three replications.)

Production functions of wheat cultivars

Production functions of different wheat cultivars (viz. KRL-1-4 and HD 2894) with potassium foliar application were developed using an output parameter such as grain yield against the input parameters pertaining to quantity and quality of irrigation water, quantity of potassium applied as foliar spray and rainfall depth during the crop growth period. Moreover, trial-and-error approach was applied in considering different easily measurable parameters besides their duration and the best production function was considered for the selected input parameters which resulted in highest R^2 value of the developed multiple regression equation. For example, in one attempt, input parameters used as independent variables were depth of one irrigation during the heading stage and the total rainfall depth up to heading stage of crop besides salinity of irrigation water and quantity of potassium sulphate fertilizer applied at heading stage. Other production functions were developed using total depth of irrigation and rainfall during the entire growing season of crops, besides the other mentioned parameters. In another attempt, the total depth of irrigation and rainfall depths up to the heading stage were used without changing the other input parameters. The coefficient of determination (R^2) values of the developed multiple regression equations were compared and the production functions with the highest R^2 were used for generation of alternative management scenarios.

Production functions developed with input and output parameters, their measured units and ranges are presented below.

Trial-I

Salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes

$$G_Y = 3.249 - 0.14S_i + 0.12D_{ib} + 0.129D_{rb} + 0.884K_{fa} \quad (R^2 = 0.82), \quad (1)$$

where G_Y is the grain yield (tonne ha^{-1}); S_i the salinity of irrigation water (dS m^{-1}), (range: $1.7 \leq S_i \leq 12$); D_{ib} the total depth of irrigation before heading stage (cm), (range: $6.1 \leq D_{ib} \leq 14.9$); D_{rb} the total depth of rainfall before heading stage (cm), (range: $1.48 \leq D_{rb} \leq 8.3$) and K_{fa} is the amount of foliar potassium application at heading stage (52% K_2SO_4 , tonne ha^{-1}), (range: $0.022 \leq K_{fa} \leq 0.425$).

Figure 5 presents the observed and predicted grain yield for salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes, potassium doses and the total depth of irrigation and rainfall before heading stage.

Salt non-tolerant cultivar HD 2894 (V_2) with foliar potassium fertigation under varying irrigation water salinity regimes

$$G_Y = 3.197 - 0.234S_i + 0.159D_{ib} + 0.129D_{rb} - 0.742K_{fa} \quad (R^2 = 0.96), \quad (2)$$

where G_Y is the grain yield (tonne ha^{-1}); S_i the salinity of irrigation water (dS m^{-1}), (range: $1.7 \leq S_i \leq 12$); D_{ib} the total depth of irrigation before heading stage (cm), (range: $6.1 \leq D_{ib} \leq 14.9$); D_{rb} the total depth of rainfall before heading stage (cm), (range: $1.48 \leq D_{rb} \leq 8.3$); K_{fa} is the amount of foliar potassium application at heading stage (52% K_2SO_4 , tonne ha^{-1}), (range: $0.022 \leq K_{fa} \leq 0.425$).

Figure 6 shows the observed and predicted grain yield for salt non-tolerant cultivar HD 2894(V_2) with foliar

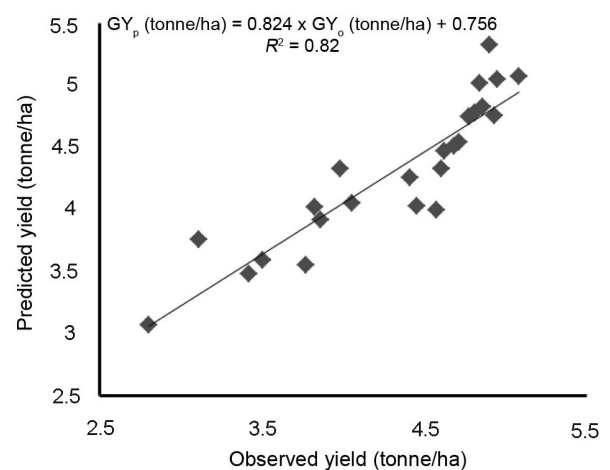


Figure 5. Predicted grain yield of salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes using the production function (eq. (1)).

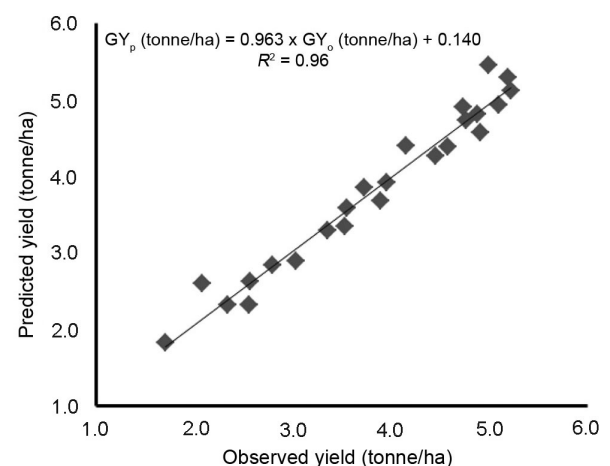


Figure 6. Predicted grain yield (production function: Trial-I) of salt non-tolerant cultivar HD 2894 (V_2) with foliar potassium fertigation under varying irrigation water salinity regimes (eq. (2)).

potassium fertigation under varying irrigation water salinity regimes, potassium doses and total depth of irrigation and rainfall before heading stage.

Trial-II

Salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes

$$G_Y = 3.827 - 0.191S_i + 0.031D_{it} + 0.077D_{rt} + 3.207K_{fa} \quad (R^2 = 0.77), \quad (3)$$

where G_Y is the grain yield (tonne ha^{-1}); S_i the salinity of irrigation water (dS m^{-1}), (range: $1.7 \leq S_i \leq 12$); D_{it} the total depth of irrigation during the cropping season (cm), (range: $13.6 \leq D_{it} \leq 33.6$); D_{rt} the total depth of rainfall during the cropping season (cm), (range: $2.2 \leq D_{rt} \leq 13.1$) and K_{fa} is the amount of potassium foliar application at heading stage (52% K_2SO_4 , tonne ha^{-1}), (range: $0.022 \leq K_{fa} \leq 0.425$).

Figure 7 shows the observed and predicted grain yield for salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes, potassium doses and total depth of irrigation and rainfall during the cropping period. It can be observed from the figure that the developed production function has R^2 value of 0.77 (lowest amongst all trials), and the prediction accuracy would be the least compared to other production functions.

Salt non-tolerant cultivar HD 2894 (V_2) with foliar potassium fertigation under varying irrigation water salinity regimes

$$G_Y = 4.229 - 0.309S_i + 0.031D_{it} + 0.071D_{rt} + 2.655K_{fa} \quad (R^2 = 0.92), \quad (4)$$

where G_Y is the grain yield (tonne ha^{-1}); S_i the salinity of irrigation water (dS m^{-1}), (range: $1.7 \leq S_i \leq 12$); D_{it} the total depth of irrigation during the cropping season (cm), (range: $13.6 \leq D_{it} \leq 33.6$); D_{rt} the total depth of rainfall during the cropping season (cm), (range: $2.2 \leq D_{rt} \leq 13.1$) and K_{fa} is the amount of potassium foliar application at heading stage (52% K_2SO_4 , tonne ha^{-1}), (range: $0.022 \leq K_{fa} \leq 0.425$).

Figure 8 shows the observed and predicted grain yield for salt-tolerant cultivar HD 2894 (V_2) with foliar potassium fertigation under varying irrigation water salinity regimes, potassium doses and total depth of irrigation and rainfall during the entire cropping period.

The developed production functions are useful in predicting grain yield scenario of KRL-1-14 and HD 2894 cultivars under varying salinity regimes, rainfall and irrigation depths before heading stage besides quantity of

potassium fertigation required for foliar spray. Many other similar possible scenarios may be developed for HD 2894 and KRL-1-4 wheat cultivars with two different inputs, viz. total depth of irrigation and rainfall with two different approaches (Trials-I and II).

The grain yield was predicted using salinity, irrigation and rainfall depths, and the quantity of potassium fertilizer for foliar spray. The dataset generated by the production functions may be useful for subsequent use by the stakeholders in enhancing grain yield under a given set of input scenarios, besides the use of quantified doses of foliar potassium fertilizer. The best production functions which gave the highest R^2 values (i.e. 0.82 for KRL-1-4 and 0.97 for HD 2894 wheat cultivars) of the developed

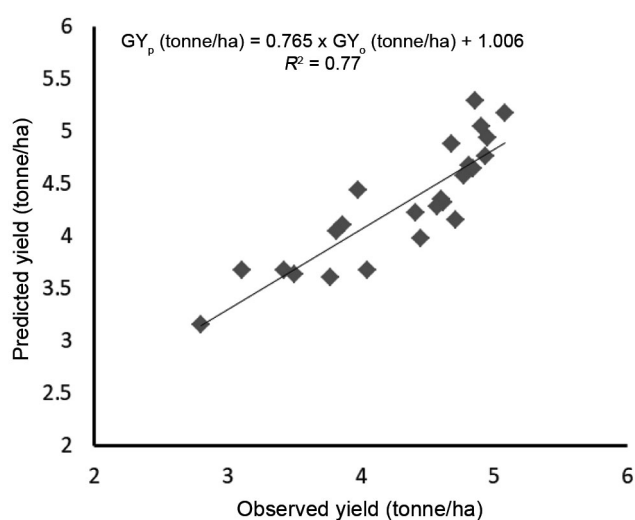


Figure 7. Predicted grain yield (production function: Trial-II) of salt-tolerant cultivar KRL-1-4 (V_1) with foliar potassium fertigation under varying irrigation water salinity regimes (eq. (3)).

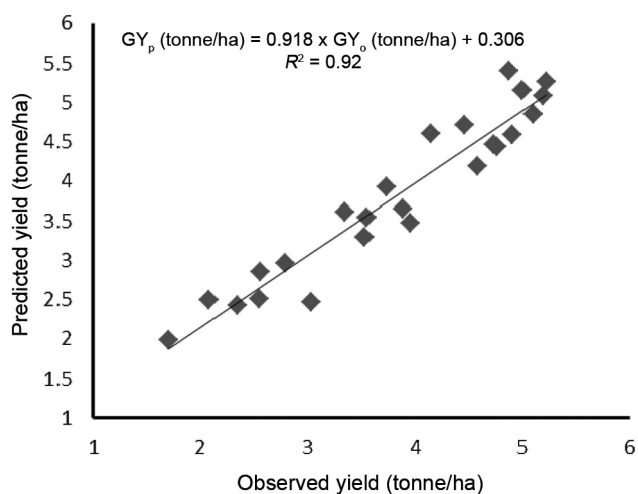


Figure 8. Predicted grain yield (production function: Trial-II) of salt-tolerant cultivar HD 2894 (V_2) with foliar potassium fertigation under varying irrigation water salinity regimes (eq. (4)).

multiple regression equations to predict grain yield (output) were associated with the input dataset pertaining to total depth of rainfall and irrigation at the heading stage, and the quantity of potassium used for foliar spray under different salinity regimes. The stakeholders can predict grain yield under different irrigation water salinity regimes and estimate the potassium doses to be applied at the heading stage of the crop using empirical models represented by eqs (1)–(4) above.

Conclusion

The protocol conceptualized in this study for the development of production functions for prediction of grain yield under different input parameters by a judicious combination of the crop model simulated and observed datasets can be replicated for other crops and cultivation methods. Further, the predicted grain yield and estimated quantity of potassium under different salinity regimes of irrigation water can be disseminated to stakeholders for enhancing the grain yield of wheat in the region. The estimation of grain yield using an empirical model under saline environment is important and may be useful to the stakeholders subject to the occurrence of similar circumstances under which the experiments have been carried out.

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