PLOS CLIMATE

RESEARCH ARTICLE

Optimizing sowing window for mungbean and its adaptation option for the South-central zone of Bangladesh in future climate change scenario using APSIM model

Faruque Ahmed[1]*, A. H. M. Motiur Rahman Talukder[1], Imrul Mosaddek Ahmed[1]*, Md. Shakhawat Hossain[2], Apurbo Kumar Chaki[3], Taslima Zahan[3], Sheikh Istiaque[3], Sohela Akhter[4], Jatish C. Biswas[5], M. Mizanur Rahman[6]

1 Plant Physiology Division, Bangladesh Agricultural Research Institute (BARI), Gazipur, Dhaka, Bangladesh, **2** On-Farm Research Division (OFRD), Bangladesh Agricultural Research Institute (BARI), Barind, Rajshishi, Bangladesh, **3** On-Farm Research Division (OFRD), Bangladesh Agricultural Research Institute (BARI), Gazipur, Dhaka, Bangladesh, **4** Tuber Crop Research Center, Bangladesh Agricultural Research Institute (BARI), Gazipur, Dhaka, Bangladesh, **5** Soil Science Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Dhaka, Bangladesh, **6** Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur, Dhaka, Bangladesh

* imrulbau@gmail.com (IMA); faruquebari@gmail.com (FA)

Abstract

Field experiment on sowing dates was carried out with BARI Mung-6 during pre-monsoon (kharif-I) season of 2021 for the evaluation of Agricultural Production Systems Simulator (APSIM) crop model. The APSIM model was parameterized using data from March 10 sowing, while validation was done with other sowing dates and data from literatures. Simulation was done with elevated temperatures (1-, 2- and 3-˚C) to find out the adaptation option against future temperature stress situations. The model was run for different sowing dates using long-term (1981–2021) historical weather data. The evaluations showed that the model performance was satisfactory in predicting crop phenology, total biomass and grain yields of BARI Mung-6. Simulated grain yields during March 10 to March 25 sowings were very similar to attainable grain yields while, very early or late sowing gave comparatively lower grain yields. The best simulated planting window was from 15 to 25 March having the highest mean grain yields with less variability over the years. Increase in temperature by 1˚C increase exhibited no significant influence on grain yields across the sowing dates, but significant yield reductions were observed with the rise of temperatures by 2 and 3˚C on March 20, March 30 and April 10 sowings. Elevated temperatures showed positive impact on grain yield of March 10 sowing only. Results revealed that optimum sowing window for mungbean is from 15 to 25 March with existing weather conditions. In future temperature rises situations, sowing of seeds by the first week of March would be one of the options to combat climate change impact on mungbean grain yield in Bangladesh.

OPEN ACCESS

Citation: Ahmed F, Talukder AHMMR, Mosaddek Ahmed I, Hossain M.S, Chaki AK, Zahan T, et al. (2023) Optimizing sowing window for mungbean and its adaptation option for the South-central zone of Bangladesh in future climate change scenario using APSIM model. PLOS Clim 2(7): e0000180. https://doi.org/10.1371/journal.pclm.0000180

Editor: Karl D. Castillo, University of North Carolina at Chapel Hill, UNITED STATES

Received: February 19, 2023

Accepted: June 26, 2023

Published: July 20, 2023

Data Availability Statement: All data can be found in the manuscript.

Funding: This work was supported by the MCCA project (CRP-II), Krishi Gobeshona Foundation (KGF). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Mungbean (*Vigna radiata* (L.) Wilczek) is the third most important summer pulse crop of Bangladesh. The optimum mean temperature for potential yield of mungbean lies between 28° and 30° C [1]. Its grains contain about ~24% easily digestible protein, provides a significant amount of fiber, antioxidants and minerals. Grains can be consumed as whole or split, as sprout or soup [2]. As mungbean grains contain a large amount of protein, it can be considered as an important component of balanced diet. Most Bangladesh households consume lentil or mungbean in their diet. But due to less acreage and low average yield of mungbean, there is a gap between its demand and supply resulting in high selling prices. In Bangladesh, mungbean occupied about 11.8% of the pulses growing areas with an average grain yield of 0.80 t ha^{-1} [3]. There is a little scope to increase production areas of mungbean to meet its demand due to the preference of rice production, the staple food crop in Bangladesh. So, one of the options would be to increase grain yield from unit area through adoption of proper agronomic practices.

Mungbean is a short duration crop which is cultivated after harvesting of dry season crops (wheat, mustard, and lentil). It can fix atmospheric nitrogen and a good source of protein. A small portion of fixed nitrogen is also utilized by the succeeding non-legume crops [4]. In farmer's field, the average grain yield of mungbean is very low due to lack of quality seed, and inappropriate agronomic management practices adopted by the farmers of which sowing date plays an important role in growth, development and grain yield. Crop establishment is greatly affected by sowing dates because of variability in weather factors, especially rainfall patterns and its amounts. Mungbean is grown in kharif-I (the major growing season from last week of February to middle of March) and kharif-II (mid-August to last week of September) seasons in Bangladesh. In the South-central zone of Bangladesh, mungbean usually suffers from untimely heavy rainfall at sowing or at emergence time that cause total crop failure. Pre-sowing heavy rain causes delay in sowing resulting in poor grain yield. Delayed sown mungbean exposed to high temperature and heavy rainfall that hamper growth and development and ultimately reduces grain yield. Delayed sown crop also faces excess rainfall at the time of reproductive phase, which is the root cause of grain yield reduction by 39–67% [5]. Under climate change situation, rainfall patterns and its amounts are changing year after year making it very difficult to follow the existing management practices for obtaining higher grain yield.

In general, optimum sowing date for individual crop is identified through field experiment over the locations which is time consuming, labor and monetary intensive processes. Crop simulation model can be used to reduce the number of field experiments in identifying optimum sowing dates for mungbean and ultimately it will be helpful for addressing climate change situations. Calibrated and validated simulation models can effectively minimize cost and time requirement for determination of suitable agricultural practices for a particular crop to be grown under diverse conditions [6, 7]. However, evaluation of a crop simulation model involves establishing confidence in its capability to predict outcomes experienced in the real world.

The APSIM model framework [8] (www.apsim.info) was selected because of its suitability for tropical and subtropical soil and crop management conditions [9, 10]. This model satisfactorily simulated yields of mungbean [11, 12]. Moreover, the model has been used successfully for simulating efficient production, improving risk management, crop adaptation, and sustainable production of different crops. To study the applicability of the APSIM model, it is necessary to test the model performance in different geographical locations for different crops. As mungbean crop module is available in APSIM, we have used this model for evaluating its performances in Bangladesh conditions. The main objectives of this study were to provide an overall assessment of the APSIM model to simulate growth and grain yield of mungbean (*var*. BARI Mung-6) as well as to find out optimum sowing window and to assess the adaptation options against future temperature stress on mungbean in the South-central zone of Bangladesh.

Materials and methods

Experiments for model calibration and evaluation

Field experiment was conducted at research field of Plant Physiology Division, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh during pre-monsoon (kharif-I) season (March to July) of 2021. The area is located at 23˚99' N latitudes and 90˚42' E longitudes.

Experimentation

A short duration (60–65 days) early maturing mungbean variety BARI Mung-6 was sown on March 10, March 20, March 30, and April 10 during kharif-I, 2021 following a Randomized Complete Block design with three replications. Each experimental unit was 3.0 m × 2.4 m with eight rows at equal spacing of 30 cm. The experiment followed BARI standard management practices to avoid stresses from water, nutrients, insect pests, and diseases. Seeds were sown @ 35 kg ha^{-1}. Before sowing, seeds and soils were treated with Provax 200-EC (@ 2.5 g powder kg^{-1} seed) and furadan 3G @ 5 kg ha^{-1} to prevent seed and soil borne diseases, correspondingly. The soil was nourished with fertilizers @ 12-12-16-8.0–1.0–0.6 kg ha^{-1} N-P-K-S-Zn-B in the form of urea, triple super phosphate, muriate of potash, gypsum, zinc sulphate, boric acid, respectively. Seeds were sown continuously in furrows made by hand rake maintaining 30 cm spacing between lines. Following the establishment of seedlings, thinning was done to maintain about 33 plants m^{-2}, weeding and other intercultural activities were performed as needed. At maturity, harvesting s done by two hand pickings of pods.

Data collection

Data on emergence, end of juvenile stage, floral initiation, flowering, pod initiation, physiological maturity were recorded/estimated. Yield and yield contributing data were recorded on whole plot basis excluding border rows. Grain and biomass yields at harvest were adjusted to 13% moisture and shown as kg ha^{-1}.

APSIM-mungbean model

Model description. The APSIM model [8] version 7.10 was used to simulate the phenological development, grain and biomass yields of tested mungbean variety. Correction factors for grain and biomass yields at 13% moisture content were incorporated in the model. The modules used genotypic coefficients of mungbean, soil water, soil nitrogen, surface residue, fertilizer, irrigation and Manager.

Input datasets. To run the simulation, daily weather, soil and crop management data were used. The weather data were grouped in a *metfile*, containing daily (i) global solar irradiation (MJ m^{-2}), (ii) air temperature (maximum and minimum) and (iv) rainfall (mm). Weather data were collected from Bangladesh Meteorological Department.

Parameterization of the APSIM model

The APSIM platform does not include the mungbean variety BARI Mung-6 (used in the field experiment), hence it was needed to parameterize in the model. Data from March 10 sowing were used for model parameterization/calibration. The required phenological parameters, based on the accumulated degree-day: 'thermal time from emergence to end of juvenile stage' (*tt_end_of_juvenile*), estimated days from emergence to floral initiation, thermal time from flowering to start grain fill, and 'thermal time requirement from the beginning of grain filling to maturity' (*tt_start_grain_fill*) were adjusted to match the simulated dates of flowering and maturity with the observed ones. An interactive approach was used to fit selected phenological data. The phenological parameters like days required for flowering and physiological maturity were calibrated first, and then the simulated grain and biomass yields were obtained for comparison with observed values. Calibration was conducted with the trial-and-error method by adjusting the simulated and observed variables [13]. Genetic coefficient was determined after obtaining a close match between observed and simulated values for total biomass, grain yield, time to reach 50% flowering, and physiological maturity. The parameterizations process was considered complete when the difference of the observed and simulated variables was minimum (RMSEn is $\geq$ 10 and $\leq$ 20%). These coefficients were used in the subsequent model validation.

Model validation

For the validation, separate APSIM simulations were run for each of the sowing dates and management conditions using the calibrated model. Observed values on grain and biomass yields from our field experiment and similar data from secondary sources [14–17] were utilized for comparison with model simulated values. The performance of the model was assessed with root mean square error (RMSE), and normalized root mean square error (RMSEn). Simulation output is considered excellent if RMSEn $<$ 10%, good when RMSEn is $\geq$ 10 and $\leq$ 20%, fair when RMSEn is $\geq$ 20 and $\leq$ 30% and poor if RMSEn is $\geq$ 30% [18].

$$RMSE = \sqrt{\left\{\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{n}\right\}}$$

$$RMSEn(\%) = \left\{\frac{RMSE}{mean\ of\ observed\ data}\right\} \times 100$$

Where n: number of observations, Pi: predicted value for the ith measurement and Oi: observed value for the ith measurement.

Sensitivity analysis

To represent climate change conditions, arbitrary changes were made by adding 0-, 1-, 2- and 3˚C to the historical daily maximum and minimum temperatures for the period of 1981–2021. To determine the sensitivity of grain yield, the crop model was first control-run with no change in temperature followed by running the model with elevated temperatures [19]. Then the results for the elevated temperatures were compared with control run.

Model application

The calibrated APSIM-Mungbean model was used to assess the long-term response of BARI Mung-6 at different sowing dates. This was done to predict the effect of different sowing dates (February 20, March 05, March 10, March 15, March 20, March 25, March 30 and April 10) on grain yields of BARI Mung-6 at Gazipur under South-central zone of Bangladesh. Probability of exceedance graphs were used to present the chance of obtaining a yield threshold under each planting window for the 41-year simulations.

Table 1. Chemical properties of experiment field soil.

Soil layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3-N (ppm)	NH_4^+ N (ppm)
0–15	6.3	0.98	0.10	12.2	1.9
15–30	6.4	0.90	0.09	10.1	2.5
30–60	6.2	0.78	0.08	9.6	2.7
60–90	6.3	0.55	0.06	7.4	3.0
90–120	6.2	0.36	0.05	5.3	3.6
120–150	6.1	0.31	0.03	3.9	4.8

https://doi.org/10.1371/journal.pclm.0000180.t001

Climate change scenarios

Climate change scenarios was developed for three elevated (1-, 2- and 3˚C) temperatures based on RCP2.6, RCP4.5, and RCP8.5, respectively [20]. Under the 'Climate Control' Toolbox of APSIM, the above said temperatures were added with daily maximum and minimum temperatures for the period from 1981 to 2021 of Gazipur location. Then the model was run with four sowing dates (March 10, March 20, March 30 and April 10) to find out the effect of elevated temperature on phenology, grain and biomass yields of mungbean. Other weather parameters were remained unchanged in the study.

Results and discussion

Soils physicochemical properties in the study sites

Soils of the experimental field belong to Grey Terrace Soil (Aeric Heplaquepts). Chemical properties of the soil is shown in Table 1.

Rainfall and temperature in model application sites

The mean monthly total rainfall, temperature and solar radiation in the model application sites across the 41-year period are presented in Table 2. Mean monthly maximum temperatures ranged from 24.94˚C (January) to 33.68˚C (April), while mean monthly minimum temperatures ranged from 12.20˚C (January) to 26.21˚C (August). The mean monthly highest total rainfall (370.47 mm) was recorded in July, while the lowest (6.48 mm) in January. Mean

Table 2. Weather data of Gazipur (41 years mean).

Month	Average temperature (˚C)		Rainfall (mm)	Solar radiation (MJ m^{-2} day^{-1})
	Maximum	Minimum		
January	24.94	12.20	6.48	13.44
February	28.31	15.07	19.29	16.32
March	32.05	19.52	48.60	19.31
April	33.68	22.94	132.50	20.93
May	33.28	24.22	280.56	20.17
June	32.62	25.82	338.81	17.63
July	31.86	26.06	370.47	16.73
August	32.29	26.21	311.33	17.20
September	32.38	25.79	286.12	15.72
October	32.02	23.83	170.78	16.05
November	29.67	18.51	27.53	14.84
December	26.11	13.96	8.57	12.85

https://doi.org/10.1371/journal.pclm.0000180.t002

Table 3. Calibrated cultivar specific parameters of BARI Mung-6.

Parameters	Acronym	Unit	Values	Remark
Thermal time from emergence to end of juvenile phase	tt_emerg_to_endjuv	˚C day	550	Calibrated
Estimated days from emergence to floral initiation	est_days_endjuv_to_init	Days	38	Calibrated
Thermal time from end juvenile to floral initiation	tt_endjuv_to_ init	˚C d	15	Default*
Thermal time from initiation to flowering	tt_floral_init_to_flower	˚C d	24	Calibrated
Thermal time from flowering to start grain fill	tt_flower_to_start_grain	˚C d	201	Calibrated
Thermal time from maturity to harvest ripe	tt_maturity_to_ripe units	˚C d	05	Default*

*Berken variety of mungbean was used as default variety

https://doi.org/10.1371/journal.pclm.0000180.t003

monthly solar radiation ranged from 12.85 to 20.93 MJ m^{-2} day^{-1} in different months of the year.

Analysis of model parameterization

Table 3 shows the estimated cultivar coefficients for BARI Mung-6. Some parameters like thermal time required from emergence to end of juvenile phase, estimated days from emergence to floral initiation, estimated days from initiation to flowering, from flowering to start grain fill and estimated days from emergence to floral initiation were calibrated, while other parameters were used as default values of Berken variety. There was good agreement between the observed/estimated and simulated values for tested phenological parameters along with grain and biomass yields (Table 4). The statistical values for the simulated and measured values varied by 1 to 6 days for RMSE with RMSEn of $<$ 10% for all phenological parameters indicating excellent calibration of the model. Similarly, RMSEn was $\geq$10% and $\leq$ 20% for grain and biomass yield respectively, which indicate good calibration of the model.

Analysis of model validation

The model validation with independent data sets for BARI Mung-6 showed good agreement between simulated and observed values for grain and biomass yields (Fig 1A & 1B). The model was able to explain grain yield variability by 94% (R^2 = 0.9415) and biomass yield by about 91% (R^2 = 0.9097). In the present investigation, the model slightly over or under estimated grain and biomass yields compared to observed data. The variations were 2 to 8% for grain yield and 2 to 5% for biomass yield. These under and over estimations of yields by the model are mostly likely depended on accuracy of calibration of the tested model [21].

Table 4. Evaluation analysis after model calibration between observed and or estimation and simulated parameters for phenological development, grain and biomass yield.

Parameters	Observed/estimated range	Mean observed/estimated	Simulated	RMSE	RMSEn (%)
Emergence (days)	5–6	5.5	5	0.58	10.18
End of juvenile stage (days)	35–37	36	38	2.16	6.00
Floral initiation (days)	38–40	39	40	1.29	3.31
Flowering (days)	39–43	41	40	1.91	4.67
Start grain filling (days)	42–46	44	46	2.58	5.86
Maturity (days)	66–78	72	69	5.74	7.98
Grain yield (kg ha^{-1})	1177–1320	1248	1366	131.83	10.56
Biomass yield (kg ha^{-1})	3550–4100	3800	4310	558.36	14.69

https://doi.org/10.1371/journal.pclm.0000180.t004

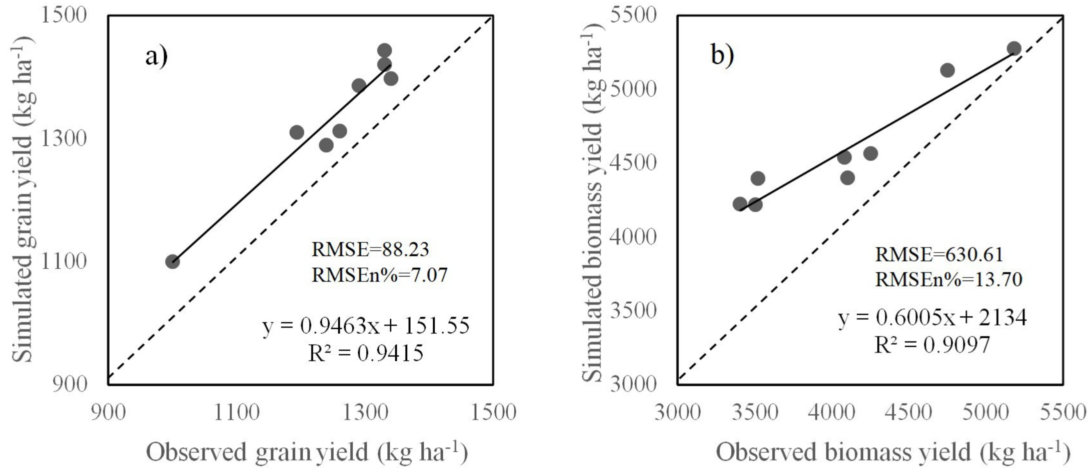

Fig 1. Comparison of observed and simulated outputs of model validation data for grain yield (A) and biomass yield (B) at varying sowing dates of BARI Mung-6.

https://doi.org/10.1371/journal.pclm.0000180.g001

Mungbean yield in different sowing dates

Box plots are showing long-term simulation (41-year period) of grain yields of BARI Mung-6 by APSIM model for eight sowing dates (Fig 2).

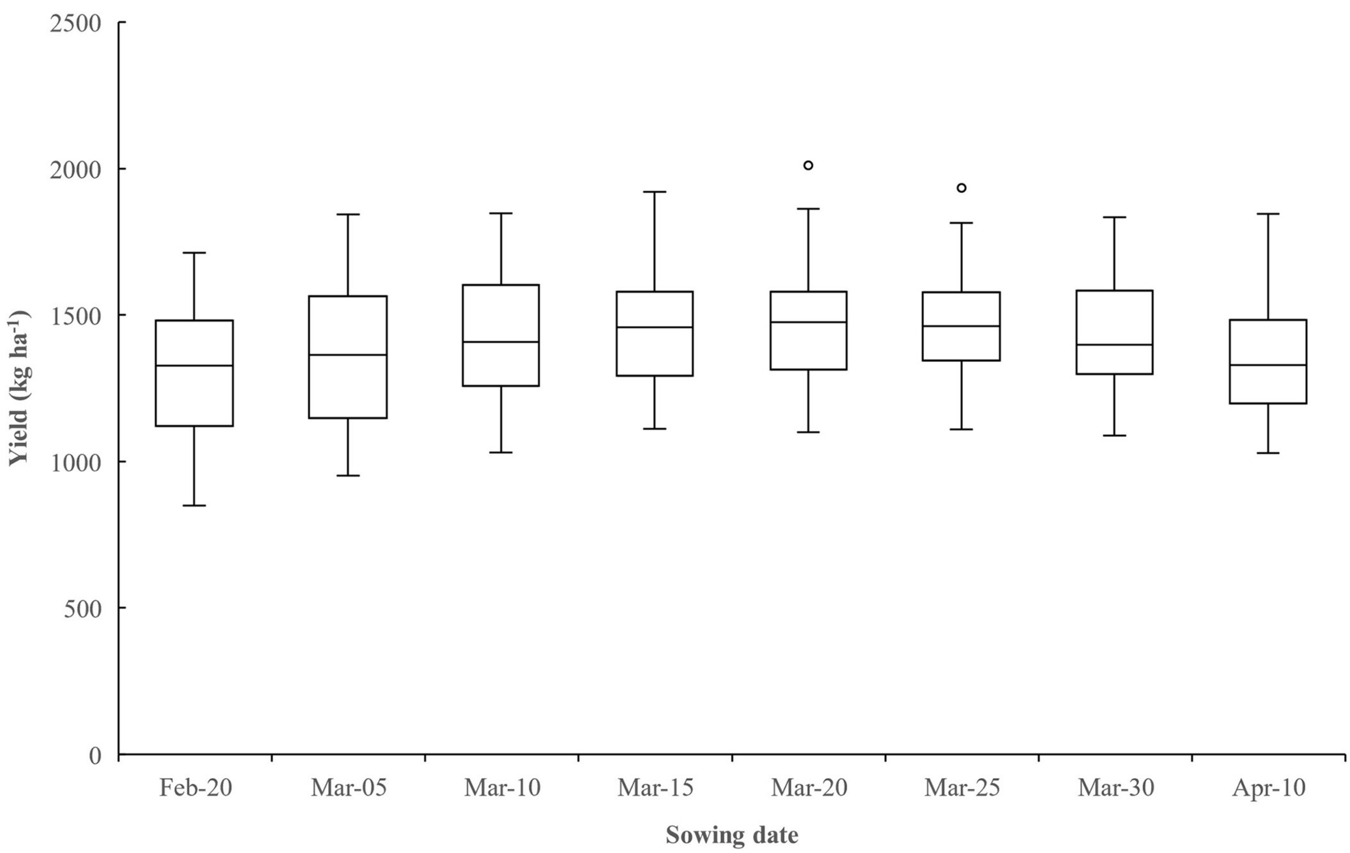

Fig 2. Simulated grain yield of BARI Mung-6 over 41 years (1981–2021). The lower whiskers indicate the lowest grain yields and the upper whiskers indicate the highest grain yields. The outliers are shown as dot points. The center black lines indicate the median values.

https://doi.org/10.1371/journal.pclm.0000180.g002

Considering median values, the grain yields reached its peak at March 20 sowing and then declined. The second highest median yield was observed in March 15 sowing. Median yields obtained from March 10 and March 25 sowings were almost similar. Grain yield ranged from 1111 to 1920 kg ha^{-1} when sown on March 15 1099 to 2011 kg ha^{-1} for March 20; 1109 to 1934 kg ha^{-1} for March 25; 1088 to 1833 kg ha^{-1} for March 30 and 1029 to 1844 kg ha^{-1} for April 10 sowings. The chance of getting lower grain yield from early sown crop was observed, while the probability of obtaining better grain yields from March 15 to March 25 seeding were observed with less variability over the years. Although we have not seen grain quality, sowing time variations influences both grin yield and grin quality. Study in tropical Australia showed that in 70% of the growing seasons, quality seeds obtained when the crop was matured after March 20, but grain yield was optimized in early January sowing dates [21]. Higher grain yield was obtained with ambient temperature than elevated temperature regimes. Such variations in seed quality and grain yields were related with weather conditions, especially rainfall and temperature variations in a particular crop growing region [22].

Probability of exceedance

The probability of exceedance was used to further assess the best sowing window based on the attainable grain yield threshold for each sowing date simulated (Fig 3). The probability of exceeding the attainable grain yield threshold of about 1,250 kg ha^{-1} would be expected to occur in >75% of the years when sowing on March 25 followed by March 20, March 30 and

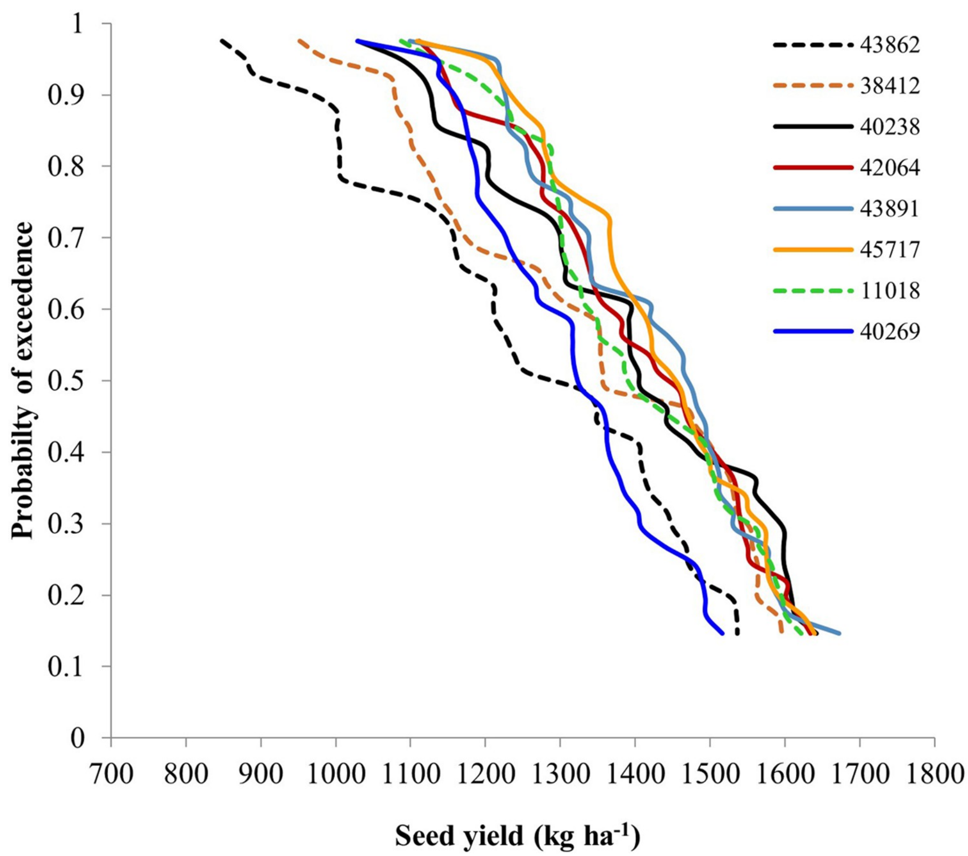

Fig 3. Probability of exceedance for simulated grain yields (1981–2021) of BARI Mung-6 across eight sowing dates in Gazipur.

https://doi.org/10.1371/journal.pclm.0000180.g003

March 15. We have found probability of occurrence of higher grain yields in 70% of the growing seasons depending on sowing times of mungbean. Such variations were related with prevailing temperature and soil moisture. Generally, early sown crops are exposed to low temperature, while the late sown crops encountered high temperatures and occasional heavy rainfall and thus crop suffers from biotic stresses [21].

Although APSIM model does not consider biotic factors, generally grain yields are influenced by both biotic and abiotic factors. Depending on crop growth stages, biotic stress influences grain yields. Existing literatures support that lower grain yields are mostly because of prevailing elevated temperature at vegetative, flowering and pod filling stages for both normal and late sowing conditions [22, 23]. Although average grain yield of mungbean in Bangladesh is about 800 kg ha^{-1}, the present investigation showed that the probability of exceeding grain yield of about 1450 kg ha^{-1} would be possible in 50% of the years when sowing on March 20, followed by March 25 and March 15. The probability of exceeding grain yield threshold of about 1070 kg ha^{-1} would be expected in >75% of the years if seeds are sown on February 20, while March 05 and April 10 sown crops would give about 1130 kg ha^{-1} and 1190 kg ha^{-1} grain yield, respectively. These results indicate that APSIM model is able to capture the grain yield differences of mungbean based on variable sowing dates. February 20 sown crop showed the least probability of obtaining better grain yield followed by April 10 sowing. So, March 15 to March 25 would be the optimum sowing window for BARI Mung-6 in Bangladesh.

Impact of elevated temperature on mungbean phenology

Mungbean phenology was greatly influenced by sowing dates and elevated temperatures (Table 5). Delayed sowing and increased temperature prolonged vegetative phase, which extended the periods of floral initiation, flowering, grain filling and maturity. Optimum temperature for vegetative phase of mungbean range from 30 to 43˚C [24]. So, 3˚C increase in temperature extended vegetative phase as it was within the optimum temperature range for growth of mungbean (Table 2). Besides, flowering of mungbean is delayed with longer photoperiods [25]. Delay sown crop received plenty of monsoon rainfall compared to early sown one (Table 2) along with increased day length. Under long crop growth duration, the flowering in mungbean is less synchronous which can arise not only because of photo-thermal sensitivity in dry matter partitioning [26], but also from soil moisture conditions [27]. High soil moisture levels encourage greater vegetative growth in mungbean [28].

In simulated condition, maturity duration was increased by 14 days because of 3˚C augmented temperature in March 10 and March 20 sowings compare to 0˚C; but it was 12 and 13

Table 5. Days required from sowing to major phenological stages of BARI Mung-6 as influenced by temperatures*.

Phenology	Sowing date											
	March 10			March 20			March 30			April 10		
	Obs.	Simulated		Obs.	Simulated		Obs.	Simulated		Obs.	Simulated	
		0˚C	3˚C		0˚C	3˚C		0˚C	3˚C		0˚C	3˚C
Emergence	6	4	4	5	4	5	4	4	5	4	4	5
Floral initiation	38	39	45	39	39	47	40	39	46	40	38	47
Flowering	39	40	46	40	40	48	41	40	47	43	39	48
Grain filling start	42	49	58	43	52	62	44	52	63	46	51	61
Maturity	66	72	86	68	72	86	78	71	83	70	69	82

*Since mungbean can tolerate up to 45˚C, only 0˚C (control) and 3˚C were considered in the simulations.

Obs. = Observed

https://doi.org/10.1371/journal.pclm.0000180.t005

days, respectively for March 30 and April 10 sowings. For reproductive phase, optimal growth takes place at 25–30˚C [24]. In the present investigation, mean maximum temperature in March was 32.05˚C and in April it was 33.68˚C (Table 2). Because of 3˚C increases in temperature, reproductive phase of mungbean would be more affected in April sowing than that of March. Under late-sown conditions, reproductive phase usually exposed to above-optimal temperature and consequently grain yield reduces due to flowers drop, less pod filling and reduced grain size [29].

Impact of elevated temperature on mungbean grain yield

With an objective of assessing the impact of climate change on mungbean production, four sowing dates, viz, March 10, March 20, March 30 and April 10 have been considered under 41 years' simulation (1981 to 2021) and presented in Fig 4. At Mach 10 sowing without temperature rise, grain yield ranged from 1030 kg ha^{-1} to 1846 kg ha^{-1} with a median yield of 1408 kg ha^{-1}. With 1˚C rise in temperature, simulated grain yields ranged from 1065 kg ha^{-1} to 1810 kg ha^{-1} with a median yield of 1430 kg ha^{-1}. Considering median values, grain yields also increased at 2˚C and 3˚C rise in temperature indicating positive impact of temperature on mungbean grain yield on March 10 sowing. At March 20 sowing with 1˚C temperature rise, grain yield variability decreased with slight declined in median grain yield; but at 2˚C rise in temperature, median grain yield was at per with no temperature rise with less grain yield variability. At 3˚C rise, slight decreased in median yield was observed with higher variability.

At March 30 sowing, a slight increase was observed in median grain yield with 1˚C rise in temperature; but at 2 and 3˚C rise, median as well as average grain yields were reduced. Similar trend was observed in 10 April sowing. Across the sowing dates, 1˚C rise in temperature showed positive impact except March 10 sowing where up to 3˚C rise showed positive impact

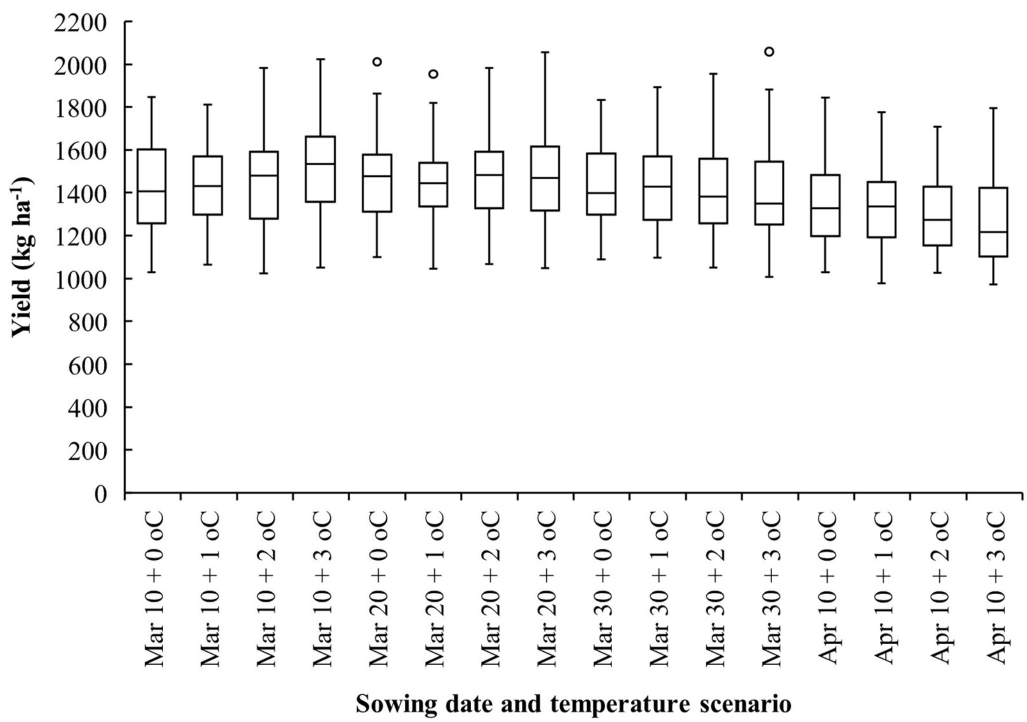

Fig 4. Effect of elevated temperature on mungbean grain yield under variable sowing dates.

https://doi.org/10.1371/journal.pclm.0000180.g004

on grain yield. Greater growth and above ground biomass yield with higher temperature indicating that mungbean is comparatively heat tolerant crop [30]. Generally, mungbean gets benefit in warmer environment of 27–30˚C and they are known for germinating and sprouting at quick rates in these conditions [31]. From the field observed data we have seen that grain size reduced by 3–20% when crop was exposed to higher temperature depending on sowing dates. However, estimation of grain size under elevated temperature was not possible with the APSIM model used (version 7.10). In the present investigation, mean minimum temperature was 12–15˚C in January and February (Table 2) indicating that temperature rise by 3˚C (as we have considered) in these months will not be optimum for growth and development of mungbean. While on the other hand, mean maximum temperature will exceed optimum limit during April and onward. These dilemmas in terms of temperature indicates that sowing in March would be comparatively favorable for mungbean cultivation in Bangladesh in future. Results from the present investigation indicate that early sowing would be one of the adaptation strategies for sustaining mungbean grain yields under climate change situation.

Conclusion

Our study focused on the response of mungbean grain yields to sowing dates and also to optimize sowing window using APSIM Mungbean Model. The simulated grain yield showed that the optimum sowing window for mungbean would be March 15 to March 25 for the South-central zone of Bangladesh. However, at elevated temperature conditions, mungbean grain yield is most likely to be more affected under late sowing conditions than in early sowing situations. Our investigation also showed that sowing of mungbean by the first week of March would be one of the options to combat climate change impact on mungbean grain yield in future in Bangladesh.

Author Contributions

Conceptualization: Faruque Ahmed, Imrul Mosaddek Ahmed.

Data curation: A. H. M. Motiur Rahman Talukder, Md. Shakhawat Hossain, Taslima Zahan, Sheikh Istiaque.

Formal analysis: A. H. M. Motiur Rahman Talukder, Md. Shakhawat Hossain, Apurbo Kumar Chaki, Sheikh Istiaque.

Investigation: Imrul Mosaddek Ahmed.

Methodology: A. H. M. Motiur Rahman Talukder, Md. Shakhawat Hossain, Apurbo Kumar Chaki, Taslima Zahan, Sheikh Istiaque.

Writing – original draft: Faruque Ahmed, A. H. M. Motiur Rahman Talukder, Imrul Mosaddek Ahmed.

Writing – review & editing: Faruque Ahmed, Imrul Mosaddek Ahmed, Taslima Zahan, Sohela Akhter, Jatish C. Biswas, M. Mizanur Rahman.

References

1. Poehlman JM. The Mungbean, Oxford and IBH Publishing Co. Pvt. Ltd, New Delhi. 1991; 27–30.
2. Tang D, Dong Y, Ren H, Li L, He CA. Review of phytochemistry, metabolite changes, and medicinal uses of the common food mungbean and its sprouts (*Vigna radiata*). Chem Cent J. 2014; 8: 4. https://doi.org/10.1186/1752-153X-8-4 PMID: 24438453
3. BBS. 2019. Bangladesh Bureau of Statistics, Statistical Yearbook of Bangladesh, Statistics Division, Ministry of Planning, GOB.

4. Sharma SN, Prasad R. Effects of sesbania green manuring and mungbean residue incorporation of productivity and nitrogen uptake of a rice-wheat cropping system. Bioresour Technol. 1999; 67(2): 171–175. https://doi.org/10.1016/S0960-8524(98)00101-1
5. Khanum MM, Bazzaz MM, Hossain MA, Huda MS, Nuruzzaman M. Effect of sowing date on performances of mungbean at BARI research field in Dinajpur. Bangladesh J Environ Sci. 2019; 37, 52–55.
6. Farage PK, Ardo J, Olsson L, Rienzi EA, Ball AS, Pretty JN. The potential for soil carbon sequestration in the tropic Dryland farming systems of Africa and Latin America: a modelling approach. Soil Till Res. 2007; 94:457–472. https://doi.org/10.1016/j.still.2006.09.006
7. Malone RW, Huth N, Carberry PS, Ma L, Kaspar TC, Karlen DL, et al. Evaluating and predicting agricultural management effects under tile drainage using modified APSIM. Geoderma. 2007; 140:310–320. https://doi.org/10.1016/j.geoderma.2007.04.014
8. Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, et al. An overview of APSIM, a model designed for farming systems simulation. Euro J Agron 2003; 18:267–288. https://doi.org/10.1016/S1161-0301(02)00108-9
9. Probert ME, Delve RJ, Kimani SK, Dimes JP. Modelling nitrogen mineralization from manures: representing quality aspects by varying C:N ratio of sub pools. Soil Biol Biochem. 2005; 37:279–287. https://hdl.handle.net/10568/71299
10. Mohanty M, Sammi RK, Probert ME, Dalal RC, Subba RA, Menzies NW. Modelling N mineralization from green manure and farmyard manure from a laboratory incubation study. Ecol Mod 2011; 222: 719–726. https://doi.org/10.1016/j.ecolmodel.2010.10.027
11. Chaki AK, Gaydon DS, Dalal RC, Bellotti WD, Gathala MK, Hossain A, et al. How we used APSIM to simulate conservation agriculture practices in the rice-wheat system of the Eastern Gangetic Plains. Field Crops Res. 2022; 275:108344. https://doi.org/10.1016/j.fcr.2021.108344.
12. Gaydon DS, Singh B, Wanga E, Poultona PL, Ahmad B, Ahmed F, et al. Evaluation of the APSIM model in cropping systems of Asia. Field Crops Res. 2017; 204: 52–75. https://doi.org/10.1016/j.fcr.2016.12.015
13. Wang J, Wang E, Feng L, Yin H, Yu W. Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crops Res. 2013; 144:135–144. https://doi.org/10.1016/j.fcr.2012.12.020
14. Puja, CD. Influence of sowing time and seed rate on the growth and yield of BARI Mung-6. 2020. Thesis (Master of Science). Sher-e-Bangla Agricultural University, Dhaka, Bangladesh. Retrieve from http://archive.saulibrary.edu.bd:8080/xmlui/handle/ 123456789/4486.
15. Afrin S, Uddin FMJ, Sarkar MAR. Responses of selected mungbean (*Vigna radiata* L.) varieties to boron fertilization. Funda Appl Agric. 2019; 4(1): 655–660. https://doi.org/10.5455/faa.815
16. Islam MN, Rahman A, Rasal-Monir M, Fatima S, Biswas S, Hoque MA. Effect of salicylic acid and $CaSO_4$ on morphological characters and yield of mungbean. Int JSci Eng Res. 2019; 10(8):1416–1426.
17. Patwary M. Growth and yield of mungbean (BARI Mung-6) as influenced by different levels of nitrogen and phosphorus. 2014. Thesis (Master of Science). Sher-e-Bangla Agricultural University, Dhaka, Bangladesh. Retrieve from http://archive.saulibrary.edu.bd:8080/xmlui/ bitstream/handle/123456789/1360/08-02888.
18. Jamieson PD, Porter JR, Wilson DR. A test of the computer simulation model ARC-WHEAT on the wheat crop grown in Zealand. Field Crops Res. 1991; 27 (4):337–350. https://doi.org/10.1016/0378-4290(91)90040-3
19. Luo QY, Kathuria A. Modelling the response of wheat grain yield to climate change: A sensitivity analysis. Theor Appl Climatol. 2013; 111(1–2): 173–182. https://doi.org/10.1007/s00704-012-0655-5
20. IPCC. Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J et al. Climate Change 2013: The Physical Science Basis. Working Group 1 (WG1) Contribution to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5), Cambridge University Press, Archived from the original on 12 August 2014. 1535 pp.
21. Yeates SJ, Lawn RJ, Adkins SW. Prediction of weather damage of mungbean seed in tropical Australia. II. Model application. Aust. J. Agric. Res., 2000; 51 (5), 649–656. http://dx.doi.org/10.1071/AR99086
22. Islam MT. Effects of high temperature on photosynthesis and yield in mungbean. Bangladesh J Bot. 2015; 44(3): 451–454, 2015. https://doi.org/10.3329/bjb.v44i3.38553
23. Chikukura L, Bandyopadhyay SK, Kumar SN, Pathak H, Chakrabarti B. Effect of elevated temperature stress on growth, yield and yield attributes of mungbean (*Vigna radiata*) in semi-arid north-west India. Curr Advan Agril Sci. 2017; 9(1): 18–22. https://doi.org/10.5958/2394-4471.2017.00003.x
24. Pasley H, Wenham K, Bell L, Huth N, Holzworth D, Chaki A, et al. APSIM next generation mungbean model: A tool for advancing mungbean production. Field Crops Res. 2023; 298: 108955. https://doi.org/10.1016/j.fcr.2023.108955

25. Imrie BC, Lawn RJ. Time to flowering of mung bean (*Vigna radiata*) genotypes and their hybrids in response to photoperiod and temperature. Exp Agric. 1990; 26 (3): 307–318. https://doi.org/10.1017/S0014479700018470.

26. Bushby H, Lawn R. Accumulation and partitioning of nitrogen and dry matter by contrasting genotypes of mungbean (*Vigna radiata* (L.) Wilczek). Aust J Agric Res. 1992; 43: 1609–1628. https://doi.org/10.1071/AR9921609

27. Thomas Robertson MJ, Fukai S Peoples MB. The effect of timing and severity of water deficit on growth, development, yield accumulation and nitrogen fixation of mungbean. Field Crops Res. 2004; 86: 67–80. https://doi.org/10.1016/S0378-4290(03)00120-5

28. Muchow R, Charles-Edwards D. An analysis of the growth of mung beans at a range of plant densities in tropical Australia. II. Seed production. Aust J Agric Res. 1982, 33 (1): 41–53. https://doi.org/10.1071/AR9820041

29. Hanumantha Rao B, Nair RM, Nayyar H. Salinity and high temperature tolerance in mungbean [*Vigna radiata* (L.) Wilczek] from a physiological perspective. Front Plant Sci. 2016; 7: 1–20. https://doi.org/10.3389/fpls.2016.00957.

30. Reardon ME, Mirwais MQ. Individual and interactive effects of temperature, carbon dioxide and abscisic acid on mungbean (*Vigna radiata*) plants. J. Plant Interac. 2017; 1291: 295–303. https://doi.org/10.1080/17429145.2017.1353654

31. Zhou L, Wu F, Zhang X, Wang Z. Structural and functional properties of Maillard reaction products of protein isolate (mungbean, *Vigna radiate* (L.)) with dextran. Intl J Food Prop. 2017; 1–13. https://doi.org/10.1080/10942912.2017.1338727