

Seed Set Patterns in East African Cooking Bananas (*Musa* spp.) are Dependent on Weather Before, During, and After Pollination

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Abstract

Background: Seed set in banana (*Musa* spp.) is influenced by weather but the most critical weather attribute(s) and the critical period are unknown. Such information is of paramount importance to increase seed set for banana breeding programs. Three female fertile East African cooking bananas (EACBs), 'Enzirabahima' (AAA), 'Mshale' (AA), and 'Nshonowa' (AA) were pollinated with the highly male fertile wild banana 'Calcutta 4' (AA). At full maturity, bunches were harvested and ripened and seeds extracted from ripe fruit pulp. Seed set was then correlated with weather before, during, and after pollination.

Results: Seed set was positively correlated with high temperatures ($r=0.172 - 0.488$), solar radiation ($r=0.181 - 0.282$) and negatively correlated with rainfall ($r=-0.214 - -0.238$) and relative humidity (RH) ($r=-0.158 - -0.438$) between 75 and 15 days before pollination (DBP). The pattern of weather association was cultivar-dependent with 'Nshonowa' having the strongest significant associations. At the time of pollination, high average temperatures were critical for seed set in 'Enzirabahima' ($r=0.214$, $P<0.01$) while high morning RH was critical for 'Mshale' ($r=0.299$, $P<0.01$). After pollination, high morning temperatures were associated with seed set ($r=0.150 - 0.429$) between 15 days to 90 days after pollination (DAP). High average temperatures were negatively correlated with seed set in 'Mshale' and 'Nshonowa' from 45 DAP to time of harvest ($r=-0.208 - -0.344$). Coefficients of correlation were generally highest 15 DBP especially for 'Mshale' and 'Nshonowa.' Principle component analysis showed that average and maximum temperature are the most important variables in the entire data set.

Conclusion: Coefficients of correlation were generally less than 0.5 partly as a result of weather involvement in seed set at several floral development stages; before, during, and after pollination. The most critical developmental stage is 15 DBP especially for 'Mshale' and 'Nshonowa' as they had the high correlation coefficients. Average temperature should be the main focus for seed set increase in banana.

Background

Conventional genetic improvement of bananas (*Musa* spp.) including plantains is challenged by poor seed set which is attributed to a combination of factors (Pillay and Tripathi, 2007). Poor seed set slows down genetic gain because breeders cannot create quickly a wide progeny base for meaningful selections. The breeding potential of the available banana gene pool has therefore not been fully exploited. Seventy eight (78) cultivars of East African Highland bananas (EAHBs) were screened for female fertility of which 37 were considered as seed fertile in Uganda (Ssebuliba et al. 2005). In plantain, 12 cultivars with relatively high seed fertility were identified in Nigeria (Swennen and Vuylsteke, 1989). Besides, among EAHBs and plantains, seed set is highly variable between genotypes and seasons (Swennen and Vuylsteke, 1989; Ssebuliba et al. 2005). Edaphic factors have also been reported to affect seed set in 'Gros Michel' with high levels of available potash and phosphate coinciding with high seed set (Shepherd, 1954). High temperatures, high solar radiation, low rainfall amounts and low relative humidity (RH) have been observed to increase seed set when plantain and EAHB flowers are pollinated manually (Ortiz and Vuylsteke, 1995; Ssebuliba et al. 2009).

Despite weather influences on seed set, weather attributes only explain so far a small percentage of variability in data. In a cross of the plantain 'Bobby Tannap' and the wild banana 'Calcutta 4,' a simple linear regression for seed set and maximum RH could only explain 31.7% (Ortiz and Vuylsteke, 1995). Correlation coefficients of weather attributes and seed set were also mostly below 0.5 for many EAHB genotypes (Ssebuliba et al. 2009). This suggests that other factors are yet to be identified when relating weather effects on seed set in banana. It is also not clear when weather most affects seed set and what attribute accounts for most of the variability. Batte et al. (2019) reported that the month of pollination had a non-significant effect on pollination success but seed set differed between years in EAHB. Moreover, variability between years is smaller than the variability between seasons or months (Ssebuliba et al., 2005). Therefore pollination success rate differences between months were expected though only differences of total seed set between years were noticed. Since onset of seasons varies between years, taking into account variability of months within years could have brought out month effects in the analyses. Cultivar differences also exist, thus analyses per cultivar could have brought out month effects much more accurately.

Weather also affects embryo germination rates. Embryos from bunches pollinated in a wet season were reported to have a higher germination rate (Vuylsteke et al. 1990). These observations call for an in-depth investigation of weather effects on seed set. However, it is noteworthy that seed fertility is a desirable trait during breeding but not in the final hybrids for consumers. Banana breeders therefore have to understand sterility in order to use it to their advantage. The aim of this study was therefore to assess the effects of weather on seed set before pollination, at the time of pollination and after pollination in selected East African Cooking Bananas (EACBs). An understanding of stages when weather is most influential and the responsible weather attributes can help in designing manipulative experiments to increase seed set thus improve breeding efficiency.

Materials And Methods

Female fertile 'Enzirabahima' (*Musa* AAA group, Matooke subgroup) and 'Mshale' and 'Nshonowa' (*Musa* AA group, Mchare subgroup) were pollinated with 'Calcutta 4' (*M. acuminata* ssp. *burmannicoides*) pollen between January 2016 and January 2019. Matooke is grown throughout the Great lakes region of East Africa including Uganda, Rwanda, and Burundi (Perrier, et al. 2019). On the other hand, Mchare is more widely adapted to different agro-ecological zones covering Madagascar, Comoros islands, Pemba and Zanzibar islands, around Mount Kilimanjaro and Mount Kenya to as far as a few spots in central Uganda (Perrier, et al. 2019). Matooke and Mchare banana types belong to the same genetic complex (Perrier, et al. 2019) and can be collectively referred to as EACBs. All pollinations were made at the National Agricultural Research Laboratories (NARL) – Kawanda station located at latitude 0° 25' N, longitude 32° 32' E at an elevation of 1,177 m above sea level. The soils at Kawanda are sandy-loams of the deep ferrallitic clay type with a pH range of 5.5–6.0 (Ssebuliba et al. 2006b). Daily weather attributes in the study period are summarized in Table 1.

The first pollination technique used was pollination as described by Vuylsteke et al. (1997). The second pollination technique was a modification of the first one by applying pollen germination media (PGM) to

enhance stigma receptivity (Waniale et al. 2020). Pollen germination media was prepared using 30 g/liter glucose along with other compounds as described by Nyine and Pillay (2007) with boric acid at 0.1 g/liter in tap water. PGM used in 2016 was 30 g/liter glucose in tap water only while complete PGM as described above was used from January 2017 to January 2019. The PGM was applied to pollen dusted on stigmas in a fine mist using a hand spray pump. At full maturity, when fingers had just started ripening (yellowing), bunches were harvested, kept in a ripening room and seed hand extracted from fruit pulp, washed, air-dried, and counted. Number of fingers per bunch was also counted and seed set was expressed on 100 fruits basis as follows;

$$\frac{\text{Total seed in a bunch}}{\text{Total number of fruit fingers of that bunch}} \times 100$$

Pearson's phenotypic correlation analyses were performed between seed set and weather data at 105, 90, 75, 60, 45, 30, 15, days before pollination (DBP), 0, 15, 30, 45, 60, 75, 90, 105, and 120 days after pollination (DAP). An assumption was made that one hand opens and is pollinated every day though up to three hands can open each day (Shepherd, 1954). At the time of pollination (0 DAP), data for weather attributes was therefore averaged for days of bunch pollination to be equivalent to number of hands per bunch. The rest of the 15 day time intervals before and after pollination were 10 day averages of weather attributes counting forward. For the cultivar 'Enzirabahima,' correlation was not run beyond 90 DAP because it matured on average 98 days from initial pollination. 'Mshale' and 'Nshonowa' matured 131 and 135 DAP respectively. To make meaningful interpretation of results, a correlation between weather attributes was run to determine inter-relationships and how they possibly interact to influence seed set. Weather data for inter-attribute relationship was 10 day averages of the weather attributes from initial date of pollination of all pollinated bunches. A principle component analysis (PCA) was run for weather attributes and seed set at the time of pollination to determine the attribute that accounts for most variability in the data. PCA was based on correlation matrix and 10 day averages of the weather attributes was considered at the time of pollination.

A multiple linear regression approach with groups was employed at every time interval considered before, during, and after pollination. The response variables (Y) was seed set per 100 fruits per bunch and weather attributes (Table 1) were explanatory variables (X). The analyses were run for each of the three cultivars and for the two pollination techniques, bunch size was taken as the grouping factor. Significant weather attributes ($P < 0.05$) from the accumulated analysis of variance (ANOVA) tables for all considered time intervals were then combined and reanalyzed using a multiple linear regression. Correlation, PCA, and multiple linear regressions were run using Genstat 19th edition (Payne, et al., 2011).

Results

Relationships between weather attributes

Solar radiation and temperature attributes were positively correlated with each other but negatively related to precipitation (rain fall and relative humidity) (Table 2 and Supplementary Table 1). There were very strong relationships between some of the weather attributes. For this reason, not all weather attributes are presented. Average temperature at 2 meters is presented for maximum temperature at 2 meters, minimum temperature at 2 meters, temperature range at 2 meters, and earth skin temperature. Their correlation coefficients with average temperature at 2 meters were 0.977, 0.864, 0.816, and 0.984 ($P < 0.001$) respectively. Precipitation attributes were also positively correlated with each other. RH at 3 pm is not presented except for a few peculiar cases.

Weather effect on seed set before pollination

Weather effects on seed set were significant right from 105 DBP when plants were still in the vegetative growth stage; these effects were few and mostly weak. High temperature recorded at 9 am was correlated with seed set ($r = 0.359$, $P < 0.001$) in 'Mshale' when the customary pollination technique was used (Supplementary Table 2). High solar radiation was required by 'Nshonowa' when pollination was done with PGM ($r = 0.214$, $P < 0.05$) while rainfall was the limiting factor for 'Enzirabahima' pollinated without PGM ($r = 0.275$, $P < 0.001$). At 90 DBP, high rainfall ($r = 0.332$, $P < 0.01$) was required particularly for 'Mshale' that was pollinated without PGM (Supplementary Table 3).

At 75 DBP, weather mainly influenced 'Nshonowa' with minimal effect on 'Mshale,' but not on 'Enzirabahima.' High average temperature and high solar radiation were positively significantly correlated to seed set in 'Nshonowa' (Supplementary Table 4). Low rainfall and RH were also required for seed set in 'Nshonowa.' At 60 DBP, high average temperatures and high solar radiation had weak effects on both Mchare cultivars when pollinated with PGM (Table 3 and Supplementary Table 5). Low rainfall only affected 'Mshale' while low RH and low temperature at 9 am increase seed set in both Mchare cultivars.

At 45 DBP, weather effects on seed set in Mchare cultivars were somewhat similar to effects 60 DBP though there was a reduced magnitude of association. On the other hand, high solar radiation ($r = 0.188$, $P < 0.05$) and low RH ($r = -0.247$, $P < 0.01$) had an effect on seed set in 'Enzirabahima' when bunches were pollinated with PGM (Supplementary Table 6). At 30 DBP, high average temperature significantly increased seed set in Mchare cultivars when pollinated with PGM (Supplementary Table 7). Low RF in Nshonowa and low RH in both Mchare cultivars increased seed set. At 15 DBP, high average temperatures, high solar radiation, and low RH had a significant effect on seed set in 'Enzirabahima' especially when pollinated with PGM. A similar pattern was observed for Mchare cultivars and 'Enzirabahima' 15 DBP. However, the correlation coefficients were generally higher for Mchare compared to 'Enzirabahima' (Table 4 and Supplementary Table 8).

Weather effect on seed set at the time of pollination and after pollination

At the time of pollination, only 'Enzirabahima' and 'Nshonowa' were positively significantly associated with high average temperatures especially when bunches were pollinated with PGM. 'Mshale' required high RH at 9 am especially for bunches pollinated without PGM (Table 5 and Supplementary Table 9). At 3 pm, low RH was required in 'Enzirabahima' especially when pollinations were made with PGM ($r = -0.260$, $P < 0.001$).

'Mshale' pollinated without PGM needed high RH ($r=0.252$, $P<0.05$) while 'Nshonowa' pollinated without PGM needed low RH ($r=-0.237$, $P<0.05$). Enhancing stigma receptivity in 'Mshale' resulted in a reduced level of association of seed set with high RH at 9 am from $r=0.299$, $P<0.01$ to $r=0.265$, $P<0.05$ (Table 5 and Supplementary Table 9).

At the stage of 15 DAP, high morning temperatures were necessary for seed set in 'Nshonowa' if pollinations were made without PGM ($r=0.350$, $P<0.001$). Interestingly, high RH at 3 pm was required for seed set in Mchare when 'Mshale' was pollinated without PGM ($r=0.328$, $P<0.01$) and in 'Nshonowa' when pollinated with PGM ($r=0.269$, $P<0.01$). On the contrary, 'Enzirabahima' needed low RH at 3 pm in bunches pollinated with PGM ($r=-0.165$, $P<0.05$). Also noted was the low solar radiation necessary for seed set in 'Nshonowa' pollinated with PGM ($r=-0.330$, $P<0.001$). A somewhat similar pattern was observed 30 DAP with all cultivars pollinated with PGM requiring high morning temperatures for seed set ($r=0.150$, $P<0.05$ for 'Enzirabahima,' $r=0.360$, $P<0.001$ for 'Mshale' and $r=0.337$, $P<0.001$ for 'Nshonowa') (Table 6 and Supplementary Table 11). Interestingly, low RH at 3 pm was somehow still associated with seed set in 'Enzirabahima' pollinated with PGM ($r=-0.170$, $P<0.05$). On the other hand, high RH at 3 pm was needed for seed set in 'Nshonowa' pollinated with PGM ($r=0.260$, $P<0.01$) and in 'Mshale' pollinated without PGM ($r=0.328$, $P<0.01$).

At 45 DAP, 'Enzirabahima' pollinated with PGM and 'Nshonowa' pollinated without PGM needed high morning temperatures for seed set ($r=0.209$, $P<0.01$ and $r=0.428$, $P<0.001$ respectively). But high average temperature reduced seed set in 'Nshonowa' pollinated with PGM ($r=-0.292$, $P<0.01$) but not in 'Enzirabahima' pollinated without ($r=0.188$, $P<0.05$) (Supplementary Table 12). Mchare additionally needed rainfall for seed set when pollinated with PGM ($r=0.298$, $P<0.01$ and $r=0.265$, $P<0.01$ for 'Mshale' and 'Nshonowa' respectively). A similar pattern was observed for Mchare 60 DAP with the exception rain (Supplementary Table 13). 'Enzirabahima' did not have the same weather attributes significant at 45 and 60 DAP. Only high temperatures at 9 am ($r=0.183$, $P<0.05$) were required for 'Enzirabahima' pollinated with PGM 60 DAP as at 45 DAP. At this point, there were only very weak but significant associations of seed set and high morning temperatures at 9 am in 'Enzirabahima' ($r=0.153$, $P<0.05$). For Mchare cultivars, the difference was that 'Mshale' pollinated with PGM needed low average temperatures at 2 meters ($r=-0.213$, $P<0.05$) and high RH at 9 am ($r=-0.250$, $P<0.05$).

A relatively similar pattern was also observed 75 DAP as observed 60 DAP with a few differences (Table 7 and Supplementary Table 14). At this point, 'Enzirabahima' pollinated with PGM also had weak but positive association ($r=0.165$, $P<0.5$) of high RH at 2 meters with seed set just like in Mchare. For 'Mshale' pollinated without PGM, high RH was associated with seed set ($r=0.220$, $P<0.05$ at 9 am. Low solar radiation ($r=-0.215$, $P<0.05$) and high RH ($r=0.237$, $P<0.05$ at 2 meters) were still significantly associated with increased seed set for 'Mshale' pollinated with PGM. For 'Nshonowa' pollinated with PGM, temperature at 9 am, low average temperature at 2 meters, low solar radiation and high RH at 3 pm were required for seed set (Table 7).

There was no weather association with seed set in 'Enzirabahima' 90 DAP as this was about its maturity time. On the other hand, high temperatures at 9 am ($r=0.300$, $P<0.01$) and high RH at 3 pm ($r=0.300$,

$P < 0.01$) were necessary for increased seed set in 'Mshale' pollinated without PGM. There were generally the same to slightly weaker associations between weather and seed set in 'Nshonowa' pollinated with PGM from 75 to 90 DAP. Weaker associations were observed for average temperature at 2 meters ($r = -0.307$, $P < 0.01$), solar radiation ($r = 0.300$, $P < 0.01$), RH at 3 pm ($r = 0.264$, $P < 0.05$), and average RH at 2 meters ($r = 0.291$, $P < 0.01$).

At 105 DAP, only high RH at 3 pm ($r = 0.385$, $P < 0.001$) was associated with high seed set in 'Mshale' pollinated without PGM (Supplementary Table 16). On the other hand, 'Nshonowa' pollinated with PGM required low average temperature at 2 m ($r = -0.304$, $P < 0.01$) for seed set. Close to full maturity at 120 DAP, weather patterns for seed set were nearly identical to those at 105 DAP (Supplementary Table 17). High RH at 9 am positively correlated to seed set in 'Mshale' pollinated without PGM ($r = 0.403$, $P < 0.001$). For 'Nshonowa' pollinated with PGM at 120 DAP, low average temperature at 2 m ($r = -0.277$, $P < 0.01$), and low solar radiation ($r = -0.347$, $P < 0.001$) were required for seed set.

Principal component analysis (PCA)

The first four principle components (PCs) could explain over 80% variability of data in 'Enzirabahima,' 84% in 'Mshale' and 84% in 'Nshonowa' (Table 8, Supplementary Tables 18 and 19). The first PC coefficients are positive for temperature related measurements and negative for precipitation related measurements in the three EACBs. But maximum and average temperature related measurements had the highest absolute coefficients in the first PC. Only RH at 9 am, RF, and temperature at 9 am seemed not to explain variability using the first PC as they had low coefficients. The first PC could explain about 51% of variability in 'Enzirabahima' and between 53 and 59% in the Mchare cultivars whether pollinations were made with or without PGM. Maximum temperature at 2 meters, average temperature at 2 meters, earth skin temperature, and temperature at 3 pm ranked as the top four for coefficients of the first PC in all three EACB. The coefficients of these first four weather attributes for the first PC were in the range of 0.341 to 0.375.

In the second PC, temperature at 9 am was the most important for 'Enzirabahima' with coefficients of 0.654 and 0.549 for pollination with and without PGM respectively. RH at 9 am was the highest in the second PC for Mchare cultivars with coefficients of 0.543 and 0.528 for 'Mshale' pollinated with and without PGM respectively. On the other hand, 'Nshonowa' had 0.634 and 0.528 for pollinations with and without PGM respectively. In the third PC for 'Enzirabahima,' RH at 9 am had the highest coefficient of 0.423 when pollinated without PGM whereas seed set per 100 fruits had the highest coefficient of 0.644 when pollinated with PGM. For Mchare cultivars, temperature at 9 am had the highest coefficients of 0.826 and 0.780 for 'Mshale' and 0.722 and 0.760 for 'Nshonowa' when pollinated with and without PGM respectively.

Multiple linear regression approach

For 'Enzirabahima' pollinated without PGM, regression analysis was only significant ($P < 0.01$) 30 DAP development stage (Supplementary Table 30). On the other hand, regression for 'Enzirabahima' pollinated with PGM was significant at all considered time intervals except at 105, 75, 15 DBP, and 15 DAP (Supplementary Tables 20 to 34). For 'Mshale' pollinated without PGM, regression was significant for all considered time intervals except at 45 and 30 DBP as well as at the time of pollination. Pollination of

'Mshale' with PGM reduced error and regression was significant at all floral development stages considered. Regression was significant for 'Nshonowa' pollinated with and without PGM except for pollination with PGM at 105 DAP (Supplementary Tables 20 to 37).

Use of PGM generally reduced the error and increased the percentage of variability accounted for in the three EACBs (Figure 1). 'Nshonowa' generally had the highest variability accounted for across considered development stages, followed by 'Mshale' and lastly, 'Enzirabahima.' For 'Nshonowa,' the highest percentage accounted for was at 45 DBP. On the other hand, percentage variability accounted for by regression in 'Mshale' pollinated with PGM was fairly consistent at all considered time intervals. Variability accounted for by regression in 'Mshale' pollinated without PGM was inconsistent across considered development stages with the lowest at 45 DBP. 'Enzirabahima' did not exceed 30% variability account for in regression analyses across all considered floral development stages whether pollinated with or without PGM. The highest percentage variability accounted for was at the time of pollination (28.7%) when pollinations were made with PGM (Supplementary Table 28). Error variability exceeded regression variability at 60, 45, 30 DBP, at time of pollination and 60 DAP for 'Enzirabahima' pollinated without PGM.

Combining significant weather attributes from accumulated ANOVA tables (Supplementary Tables 38 to 55) from all considered floral development in a multiple linear regression with bunch size as groups revealed significance. Only 'Mshale' pollinated with and without PGM was revealed bunch size as a significant grouping factor (Table 9). The highest total variability accounted of 96.7% for came from 'Mshale' pollinated with PGM. For 'Nshonowa' pollinated with PGM, there were a total of 90 counts of significant weather attributes at various stages. But all these counts of significant weather attributes could not all be accommodated in the fitted model. Consequently, earth skin temperature and temperature range were dropped for average temperature at 2 meter and temperature range at 2meters was dropped for maximum temperature at 2 meters. Their correlations were $r=0.984$, $P<0.001$ and $r=0.916$, $P<0.001$ respectively.

Relating correlation, PCA and multiple linear regression

PCA teased out maximum and average temperature at 2 meters as the most important weather attributes for seed set. Regression also revealed that use of PGM increase percentage variability accounted for by the regression model. A plot of correlation coefficients of seed set with average temperature at various development stages for the three EACB pollinated with PGM was therefore used describe the ideal trend for seed set (Figure 2). The three EACB seemed to follow a similar pattern though Mchare cultivars were more closely related. Mchare cultivars had two peaks of positive temperature correlation with seed set before pollination. The first and lesser peak happens between 75 and 60 DBP while the second and greater peak happens at 15 DBP. 'Enzirabahima' had a lesser peak about 45 DBP and greater peak at 15 DBP and time of pollination. After pollination, low average temperatures are generally required for seed set especially for Mchare. The magnitude of temperature association with seed set after pollination is less than before pollination (Figure 2).

Discussion

All considered weather attributes were in one way or another significantly associated with seed set at some floral development stage. Weather plays a role before pollination, at the time of pollination, and after pollination. However, weather requirements for seed set vary depending on the stage of development and to a considerable extent, the cultivar. Consequently, the nature of association of weather attribute with seed set is not the same at different developmental stages. From 75 and 15 DBP and during pollination, low precipitation attributes and high temperature attributes were generally associated with high seed set. High temperature has been attributed to proper bunch development (Simmonds, 1962) and this is what was observed in the current study. Between 15 DAP to about 10 days before harvest maturity, weather requirements for seed set generally reversed compared to requirements before and during pollination.

High rainfall, RH, and morning temperature were the weather attributes that significantly correlated with seed set between 105 and 90 DBP. These are likely requirements to increase bunch size which was linked to higher seed set in 'Gros Michel' (Shepherd 1954). Multiple linear regressions were significant for bunch size at several stages of development especially in Mchare. Bunch size therefore has an influence on seed set but these effects may be dependent on other factors like weather and the cultivar. This was revealed in 'Mshale' as it was the only cultivar that had significant bunch size effects in the multiple linear regression models that combined significant weather attributes from regression at all considered time intervals.

Edaphic factors were also suggested by Shepherd (1954) to be involved in seed set. Particularly, available potash and phosphate in the soil coincided with highest seed set even if the bunches were not big. Of the 3 EACBs, 'Nshonowa' had the highest correlation coefficients at 75 DBP which suggests genetic differences. This may be the period of bunch initiation at the growing apex of 'Nshonowa,' about 11 leaves are said to be inside the pseudostem when bunch initiation happens (Turner, et al. 2007). For 'Mshale,' a similar pattern as in 'Nshonowa' was observed 60 DBP which may be its time for bunch initiation. Besides the observed pattern, low temperatures at 9 am increased seed set in Mchare cultivars. It is ironic and unclear why low minimum temperatures were required for seed set in Mchare 60 DBP.

On the other hand, the significant effect of high solar radiation and low RH on seed set in 'Enzirabahima' 45 DBP may be the time of its bunch initiation. The magnitude of association was lower in 'Enzirabahima' compared to Mchare which suggests more variables involved in seed set for 'Enzirabahima.' The non-significant month effects for pollination success observed by Batte, et al. (2019) could have been a result of differences in maturity of the EAHBs. 'Enzirabahima' matured in 98 days, 'Mshale' in 131 and 135 days for 'Nshonowa.' These differences may also be reflected in development stages, 2 of 12 considered weather attributes were significantly associated with seed set in 'Mshale' 75 DBP. On the other hand, 9 of 12 considered weather attributes had a significant effect on seed set in 'Nshonowa' while 'Enzirabahima' had none. However, at 60 DBP, 8 of 12 considered weather attributes became associated with seed set in 'Mshale' and 9 of 12 for 'Nshonowa,' 'Enzirabahima' still had none.

These differences may portray same weather conditions having different effects on fertility because of differences in developmental stages even if flowering is at the same time. The month pollination effects could have therefore been confounded within pooled cultivars in Batte, et al. (2019). Also as demonstrated in this study, some weather effects could not be detected after pooling the 3 EACBs (Data not presented).

Non-significant month effects for pollination success could have also been as a result of differences in weather of the same months in different years over the 21 year period. And since pollination success is presence or absence of seed rather than number of seeds, month effects may have been masked. It may therefore be better to consider number of seed rather than pollination success when evaluating weather effects on fertility in *Musa*. Ssebuliba et al. (2009) who considered three years found differences in seed production of EAHBs in different months but years were non-significant.

Bunch initiation time may follow the order of time to maturity with late maturing genotypes having the longest time between likely bunch initiation and time of flowering. The lower association of weather and seed set in 'Enzirabahima' 30 DBP may reflect less critical developmental processes. This was also observed in Mchare between 45 to 30 DBP. Peak weather involvement in seed set was about 15 DBP and this may be the most critical stage of bunch developmental stage. Correlation coefficients were highest at this stage. This is the likely stage when embryo sac differentiation takes place because low temperatures lead to embryo sac malformation (Turner, et al. 2007) and consequently low seed set. The bunch is likely to be in the vertical position but it has not cleared the pseudostem, ovule differentiation is active with meiosis taking place in both diploids and triploids (Fortescue and Turner, 2005).

Pollinations are usually done between 7 am and 10 am and pollen germinates within 3 hours. High average temperatures which are usually after 2 pm are therefore less likely to be involved in pollen germination. But high temperatures have been reported to overcome self-incompatibility in citrus (Kawano et al. 2016) and in apples (Yoder, et al. 2009). In this current study, increase of seed set as a result of high average and maximum temperatures at the time pollination may be responsible for overcoming pollen tube inhibition especially in 'Enzirabahima' and 'Nshonowa.' This may partly be in agreement with observations made by Soares et al. (2014) who observed a necrosis at the tip of the ovary which forms much sooner in triploids than in diploids. This is likely to be the area where pollen tubes are arrested before reaching the ovules. But these results also suggest that pollen tube inhibition maybe cultivar dependent in diploids as 'Mshale' did not need high temperature at the time of pollination. For this reason, it is highly likely that the temperature is the most important weather attribute at the time of pollination for cultivars with residual fertility.

The high RH at 9 am required by 'Mshale' for increased seed set especially when pollinated without PGM suggests its requirement for pollen hydration. This observation was made possible after deliberately not bagging bunches during pollination from January 2017 to the end of the experiment. This may explain observations made by Shepherd (1954) of delayed pollen tube entry into the style by an hour. He also observed increased seed set when pollinated bunches of 'Gros Michel' were kept in a moist environment soon after pollination. This may favor pollen hydration and consequently germination on the stigma. This particular observation also brings to question the bagging material used under different weather conditions. It is a common practice to use polyethylene bags during rainy seasons and cotton bags during the hot seasons as polyethylene scorches the bunch in hot conditions. The way forward would be to use polyethylene bags to create a humid environment around the bunch especially for pollinations in hot season; creating a shade from direct sunlight maybe necessary.

It was evident that PGM was helpful to control some of the formerly unknown source of variation that was previously veiled in similar studies. The liquid PGM provided extra moisture on the stigma for quick pollen hydration. The components in the media stimulated quick pollen germination as revealed in a parallel study (Waniale et al. 2020). This suggests that pollen germination on the stigma can be a limiting factor as revealed by data from Simmonds (1952). Some self-pollinations of *Musa acuminata* clones yielded less seed than crosses implying that there are some levels of pollen compatibility on stigmas in banana. Batte, et al. (2019) found that 'Calcutta 4' pollen was not the most efficient for screening female fertility in EAHBs yet it has one of the highest *in vitro* pollen germination rates. Plantains have also shown differential seed set when pollinated with *M. balbisiana* and 'Calcutta 4' whose pollen viabilities are deemed high (Swennen and Vuylsteke, 1989).

After pollination, high temperatures in the morning could be critical for physiological processes of embryogenesis and initial seed development in EACB. As maturity period approached, Mchare switched from high to low morning temperature in order to set seed. Low solar radiation, low average daily temperature at 2 meters coupled with high RH may suggest critical physiological processes necessary for seed development. Since average temperatures are negatively correlation with RH, it may be hard to tell whether both high temperatures and low RH play a role in seed set after pollination. Nonetheless, it is likely that these conditions slow down photosynthetic rate which ultimately slows fruit filling rate. These conditions may also slow that evapotranspiration rate which results in slow movement of materials in the plant especially from the leaves and roots to the stem and bunch. This may favor resource allocation to the seed rather than the fruit pulp. Interestingly, Shepherd (1954) found fruit circumference to be negatively correlated to seed set in 'Gros Michel.'

Events that happen after pollination may be responsible for whether seed develops into good or bad seed, seed with or without an embryo and embryo germination rates. Vuylsteke et al. (1990) reported high embryo germination rates in plantains following pollination in the wet season. Results from this current study do concur with Vuylsteke et al. (1990) findings as high precipitation after pollination favour seed set in EACB. But it has to be noted that high precipitation attributes have to come just after low precipitation. It could also be possible that high rate of fruit filling may have huge implications on seed fertility in *Musa*. Matooke has low seed set with poor embryo recovery and germination (Ssebuliba, et al. 2006a) and it matures much earlier than Mchare. Ssebuliba, et al. (2006a) also found differences among Matooke cultivars for percentage hard black seed, embryo recovery and embryo germination. These differences reflect genetic diversity in Matook and could be correlated with days to maturity.

Though maximum temperature and average temperature measurement accounted for the most variability in data, they may not be entirely responsible for seed set in *Musa*. Nonetheless, they were consistently ranked highest by the first PC in EACB pollinated with or without PGM. This implies that temperature is the highest contributor to seed set in EACBs and can be inferred to other banana types. Maximum and average temperature are the most important weather attributes as they are highly correlated with weather attributes with the highest coefficients in the first PC. Only RH at 9 am, RF, and temperature at 9 am had weak correlation with maximum and average temperature at 2 meters with correlation coefficients of less than 0.6 and PC coefficients of less than 0.2 in the first PC. Temperature at 9 am and RH at 9 am were the

highest ranked in the second and third PCs for the three EACB whether pollinated with or without PGM. This suggests that banana improvement programs have to consider manipulating maximum and average temperature for increased seed set. This current study showed that use of PGM addresses requirements of high RH in the morning. Maximum and average temperature at 2 meters generally had the highest coefficients in the first PCs across development stages which suggest careful selection of the pollination station. Shepherd, (1954) observed that a pollination station situated at the coast had higher average seed per bunch compared to that in the sheltered valley. But the few fertile bunches from the pollination station in the sheltered valley were highly fertile. This observation in 'Gros Michel' may point to the importance of high temperature before pollination as observed at the coast. Conversely, importance of low temperature after pollination explains the observations of the pollination station in the sheltered valley. Taking into consideration temperature requirements before and after pollination will potentially increase seed set, embryo rescue and germination rates.

The regression model used could hardly account for variability in all considered development stages in 'Enzirabahima.' This implies that there are other major factors that limit seed set in 'Enzirabahima.' If these unknown factors were identified and addressed, weather effects on seed set in 'Enzirabahima' would become more apparent. The highest variability accounted for by regression in 'Enzirabahima' was at the time of pollination which may suggest where the biggest limiting factor(s) occurs. Correlation revealed high temperatures at the time of pollination especially when pollinations are made with PGM to be positively associated with seed set. Pollen tube growth may therefore be the biggest seed set limiting factor in 'Enzirabahima' (3x) compared to Mchare (2x) (Soares et al. 2014). For 'Mshale,' pollination with PGM increased percentage variability explained by the regression model which was generally consistent at all considered development stages. This suggested that using a regression approach may not be the most effective way of pin pointing the most critical stage for weather involvement in seed set. Nonetheless, most variability accounted in 'Mshale' for by the regression model was at 90, 105, and 120 DAP with over 70% of variability explained. 'Nshonowa' had the highest percentage variability explained by the regression model across all considered development stages. This suggested weather effects on seed set in 'Nshonowa' are very paramount for seed set.

Weather involvement in seed set in EACBs after pollination suggests ovule abortion and seed development issues which results in fluffy seed. Banana breeding programs may have to devote some efforts into determining the appropriate time of harvest for maximum embryo rescue and germination rates. This may also suggest that using the sinking-floating criteria to screen for seed with embryos may not be the best method. Only seeds that sink in water are said to contain embryos.

Combining significant weather attributes from accumulated regression ANOVA tables of considered development stages showed an overall increase in regression accuracy. This confirms weather involvement in seed set before, during, and after pollination. Ortiz and Vuylsteke, (1995) only observed 31.7% of variability explained by a simple linear regression of maximum RH and seed set of a cross between plantain 'Bobby Tannap' and wild banana 'Calcutta 4.' The low variability accounted for by the regression model was a result of considering only the time of pollination and only RH in regression model.

And as observed in this study, maximum and average temperatures are the most important for seed set rather than RH.

A plot of correlation coefficients of average temperature with seed set therefore against floral developmental stages summarized the general trend required for seed set. But the likelihood that nature provides these specific conditions is slim. Besides, pollination is a continuous process thus most bunches are pollinated when conditions are not favorable for seed set. This consequently resulted in the low correlation and PC coefficients. Also as observed, bunch size has an effect on seed set thus bulking different bunch sizes in the same analysis reduces precision.

Conclusions

Specific weather attributes for different cultivars are required for seed set from about 75 DBP to the time of full fruit maturity. Generally, low precipitation attributes and high temperature attributes are required before pollination and at the time of pollination. However, high RH at 9 am and at 3 pm is a prerequisite for 'Mshale' but not 'Nshonowa' and 'Enzirabahima' at the time of pollination. After pollination, high precipitation and low average temperatures are generally required for seed set in Mchare. On the other hand, 'Enzirabahima' needed low precipitation and high temperature after pollination. But since a regression model could explain over 85% of variability in Mchare and about 13% in 'Enzirabahima,' weather requirements for seed set in Mchare are more reliable. The most important weather attribute for seed set is maximum temperature as pointed out by PCA. A relatively easy solution to increasing seed set in *Musa* will therefore depend on identifying close to ideal environments for high seed set. Breeders will also have to make necessary manipulations on critical weather attributes at specific floral development stages. As observed, a single approach will not overcome sterility but rather, a holistic approach. Besides providing favorable temperature for inflorescent development, ensuring good conditions for pollen germination and fine-tuned media specifically for embryo germination will improve breeding efficiency. Seasonality effects on fertility in *Musa* have mainly focused on the time of pollination but it turned out that the most critical stage is 15 DBP. These findings can be used for increased efficiency of breeding EACBs and other *Musa* spp.

Abbreviations

EACBs: East African cooking bananas; EAHBs: East African Highland bananas; AAA: Triploids with an A genome; AA: Diploids with an A genome; r: correlation coefficient; DBP: days before pollination; DAP: days after pollination; PGM: Pollen germination media; NARL: National Agricultural Research Laboratories; NASA: National Aeronautics and Space Administration; T@3pm: Temperature at 3 pm; T@9am: Temperature at 9am; T2M: Average temperature at 2 meters; T2MMax: Maximum temperature at 2 meters; T2MMin; Minimum temperature at 2 m; T2MRange: Temperature range at 2 meters; TS: Earth skin temperature; RH: Relative Humidity; RH@3pm: Relative humidity at 3 pm; RH2M: Relative humidity at 2 m; Sol. Rad.: Solar radiation; RF: Rainfall; Tec1: Pollination as described by Vuylsteke et al. (1997); Tec2: Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media; Enz:

'Enzirabahima'; Msh: 'Mshale'; Nsh: 'Nshonowa'; PCA: principal component analysis; PC: principle component; Lat. Roots: latent roots; Var. (%): Percentage variation; ANOVA: Analysis of variance; and r^2 : Percentage variability accounted for by the linear regression model.

Declarations

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Authors' contributions

Conception of research idea and designing experiments: AW, RS. Performed experiments, analyzed data and wrote the paper: AW. Contributed materials: RT, JK, WKT. All authors reviewed and commented on the paper before submission.

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Availability of data and information

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1

Daily weather attributes between January 2016 and January 2019 at the National Agricultural Research Laboratories

Weather attribute and data source	Maximum	Minimum	Average
Temp at 9 am (°C) – NARL	22.1	14.5	17.9
Temp at 3 pm (°C) – NARL	35.0	21.0	28.8
Temp Max at 2 meters (°C) – NASA	32.2	20.5	26.0
Temp Min at 2 meters (°C) – NASA	24.3	15.9	20.5
Temp range at 2 meters (°C) – NASA	13.0	1.6	5.5
Average temp at 2 meters (°C) – NASA	27.6	19.5	23.2
Earth skin temp (°C) – NASA	28.6	21.0	24.2
Solar radiation (kW-hr/m ² /day) – NASA	7.5	0.7	5.2
Relative humidity at 9 am (%) – NARL	100.0	52.0	89.4
Relative humidity at 3 pm (%) – NARL	100.0	24.0	71.5
Average RH at 2 meters (%) – NASA	89.4	41.3	70.2
Rainfall (mm) – NARL	103.6	0.0	1,314.5 (Annual)
Source: NARL meteorological department and NASA website (https://power.larc.nasa.gov/data-access-viewer/). The accuracy of NASA weather data is to an area of half a degree.			

Table 2
Correlation between selected weather attributes at the time of pollination of EACBs

	T@3 pm	T2M	T2MMax	T2MMin	T2MRNG	TS	RH@3 pm
T2M	0.895	-					
T2MMax	0.889	0.977	-				
T2MMin	0.728	0.864	0.752	-			
T2MRNG	0.778	0.816	0.916	0.424	-		
TS	0.861	0.984	0.969	0.838	0.820	-	
RH@3 pm	-0.646	-0.601	-0.627	-0.450	-0.587	-0.552	-
RH2M	-0.708	-0.785	-0.842	-0.548	-0.823	-0.770	0.554
<p><i>All correlation coefficients significant at $P < 0.001$, T@3 pm – Temperature at 3 pm, T2M – Average temperature at 2 meters, T2MMax – Maximum temperature at 2 meters, T2MMin – Minimum temperature at 2 meter, T2MRNG – Temperature range at 2 meters, TS – Earth skin temperature, Sol. Rad. – Solar radiation, RH@3 pm – Relative humidity at 3 pm, RH2M – Relative humidity at 2 m.</i></p>							

Table 3
Correlation of weather attributes with seed set in EACBs 60 DBP

	T@9am	T2M	Sol. Rad.	RF	RH@9am	RH2M	n
Enz tec1	0.150	0.044	0.038	-0.058	0.052	0.060	158
Enz tec2	0.037	0.000	-0.042	0.035	0.022	-0.010	174
Msh tec1	0.136	0.170	0.247*	-0.214*	0.016	-0.228*	92
Msh tec2	-0.283**	0.263*	0.121	-0.002	-0.001	-0.368***	90
Nsh tec1	-0.029	0.252*	0.045	-0.040	0.041	-0.248*	90
Nsh tec2	-0.198*	0.389***	0.249*	-0.048	0.149	-0.438***	100
<p><i>*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH2m – Relative humidity at 2 meters, n – Number of observations, Tec1 – Pollination as described by Vuylsteke et al. (1997), Tec2 – Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media (PGM), Enz – ‘Enzirabahima,’ Msh – ‘Mshale,’ and Nsh – ‘Nshonowa.’</i></p>							

Table 4
Correlation of weather attributes with seed set in EACBs 15 DBP

	T@9am	T2M	Sol. Rad.	RF	RH@9am	RH2M	n
Enz tec1	0.036	0.064	-0.008	-0.144	-0.017	-0.069	158
Enz tec2	0.149*	0.196**	0.192*	-0.077	-0.122	-0.111	174
Msh tec1	-0.122	0.182	0.172	-0.238*	-0.148	-0.329**	92
Msh tec2	0.164	0.421***	0.161	-0.200	0.000	-0.373***	90
Nsh tec1	0.082	0.182	0.154	-0.053	0.055	-0.084	90
Nsh tec2	0.121	0.487***	0.236*	-0.074	-0.038	-0.434***	100
<p><i>*P < 0.05, **P < 0.01, ***P < 0.001, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH2m – Relative humidity at 2 meters, n – Number of observations, Tec1 – Pollination as described by Vuylsteke et al. (1997), Tec2 – Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media (PGM), Enz – ‘Enzirabahima,’ Msh – ‘Mshale,’ and Nsh – ‘Nshonowa.’</i></p>							

Table 5
Correlation of weather attributes with seed set in EACBs at pollination time

	T@9am	T2M	Sol. Rad.	RF	RH@9am	RH2M	N
Enz tec1	0.027	0.102	0.078	-0.023	-0.062	-0.109	158
Enz tec2	0.122	0.214**	0.181*	-0.001	-0.071	-0.154*	174
Msh tec1	-0.017	0.060	-0.030	0.059	0.299**	-0.093	92
Msh tec2	0.148	0.120	-0.029	0.139	0.265*	-0.020	90
Nsh tec1	-0.065	0.223*	0.220*	-0.083	0.030	-0.224*	90
Nsh tec2	-0.063	0.201*	-0.099	0.057	0.129	-0.151	100
<p><i>*P < 0.05, **P < 0.01, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH2m – Relative humidity at 2 meters, n – Number of observations, Tec1 – Pollination as described by Vuylsteke et al. (1997), Tec2 – Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media (PGM), Enz – ‘Enzirabahima,’ Msh – ‘Mshale,’ and Nsh – ‘Nshonowa.’</i></p>							

Table 6
Correlation of weather attributes with seed set in EACBs 30 DAP

	T@9am	T2M	Sol. Rad.	RF	RH@9am	RH2M	n
Enz tec1	-0.141	0.010	-0.112	-0.037	0.068	-0.080	158
Enz tec2	0.150*	0.079	0.043	0.118	0.015	0.020	174
Msh tec1	0.121	0.014	0.189	0.000	0.305**	0.035	92
Msh tec2	0.360***	-0.094	0.011	0.149	0.122	0.208*	90
Nsh tec1	0.207	-0.013	-0.107	-0.059	0.004	0.101	90
Nsh tec2	0.337***	-0.104	-0.249*	0.023	0.150	0.231*	100
<p><i>*P < 0.05, **P < 0.01, ***P < 0.001, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH2m – Relative humidity at 2 meters, n – Number of observations, Tec1 – Pollination as described by Vuylsteke et al. (1997), Tec2 – Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media (PGM), Enz – ‘Enzirabahima,’ Msh – ‘Mshale,’ and Nsh – ‘Nshonowa.’</i></p>							

Table 7
Correlation of weather attributes with seed set in EACBs 75 DAP

	T@9am	T2M	Sol. Rad.	RF	RH@9am	RH2M	n
Enz tec1	0.012	-0.085	-0.113	-0.043	0.069	0.095	158
Enz tec2	0.175*	-0.072	-0.097	0.057	0.028	0.165*	174
Msh tec1	0.078	-0.093	-0.087	-0.056	0.220*	0.084	92
Msh tec2	0.168	-0.191	-0.215*	-0.095	0.231*	0.237*	90
Nsh tec1	0.166	-0.086	-0.099	0.006	0.109	0.115	90
Nsh tec2	0.239*	-0.340***	-0.328***	-0.112	0.179	0.409***	100
<p><i>*P < 0.05, ***P < 0.001, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH2m – Relative humidity at 2 meters, n – Number of observations, Tec1 – Pollination as described by Vuylsteke et al. (1997), Tec2 – Pollination tec1 with modifications of enhanced stigma receptivity with pollen germination media (PGM), Enz – ‘Enzirabahima,’ Msh – ‘Mshale,’ and Nsh – ‘Nshonowa.’</i></p>							

Table 8
Coefficients of four PCs of 13 variables of weather attributes and seed set in 'Enzirabahima'

Pollination Technique 1					Pollination Technique 2				
	PC1	PC2	PC3	PC4		PC1	PC2	PC3	PC4
T2MMax	0.375	-0.016	0.192	-0.044	T2MMax	0.375	0.048	-0.159	0.022
T2M	0.374	0.092	0.156	0.026	T2M	0.372	0.145	-0.096	-0.057
TS	0.360	0.094	0.252	0.025	TS	0.358	0.171	-0.181	-0.019
T@3 pm	0.359	0.054	-0.097	0.036	T@3 pm	0.354	0.007	0.061	-0.007
RH2M	-0.321	0.293	-0.196	-0.016	T2MRange	0.320	-0.145	-0.253	0.158
T2MRange	0.318	-0.226	0.216	-0.168	RH2M	-0.319	0.254	0.157	0.049
T2MMin	0.279	0.338	0.057	0.183	Sol. Rad.	0.296	-0.102	0.128	0.151
Sol. Rad.	0.266	-0.020	-0.398	0.080	T2MMin	0.291	0.314	0.051	-0.189
RH@3 pm	-0.253	-0.083	0.399	0.138	RH@3 pm	-0.254	0.098	-0.348	-0.102
RF	-0.172	0.260	0.365	-0.224	RH@9am	-0.090	0.532	-0.307	0.002
T@9am	0.082	0.654	-0.345	-0.036	RF	-0.079	0.388	-0.230	0.728
RH@9am	-0.062	0.467	0.423	-0.194	T@9am	0.046	0.549	0.372	-0.396
Seed/100fr	0.057	-0.091	-0.169	-0.905	Seed/100fr	0.103	0.085	0.644	0.461
Lat. roots	6.655	1.545	1.198	1.024	Lat. roots	6.708	1.737	1.085	0.934
Var. (%)	51.19	63.08	72.30	80.18	Var. (%)	51.60	64.96	73.31	80.50
Trace	13				Trace	13			
<p><i>T@3 pm – Temperature at 3 pm, T@9am – Temperature at 9am, T2M – Average temperature at 2 meters, T2MMax – Maximum temperature at 2 meters, T2MMin – Minimum temperature at 2 meters, T2MRange – Temperature range at 2 meters, TS – Earth skin temperature, Sol. Rad. – Solar radiation, RF – Rainfall, RH@9am – Relative humidity at 9am, RH@3 pm – Relative humidity at 3 pm, RH2m – Relative humidity at 2 meters, Lat. Roots – Latent roots, Var. (%) – Cumulative percentage variation, Pollination Technique 1 – Pollination as described by Vuylsteke et al. (1997), Pollination Technique 2 – Pollination Technique 1 with modifications of enhanced stigma receptivity using pollen germination media (PGM).</i></p>									

Table 9
Multiple linear regression ANOVA of significant weather attributes regressed on seed set in EACBs

Source	Enz tec1	Enz tec2	Msh tec1	Msh tec2	Nsh tec1	Nsh tec2
Regression (m.s)	56.7*	53.4*	1,038.6***	2,128.7***	88.8***	221.8**
Residual (m.s)	28.1	31.4	110.5	63.3	9.8	30.1
Change (m.s)	26.2	46.3	401.5*	1,121.3***	5.8	86.9
Regression (d.f)	18	32	68	72	59	82
Residual (d.f)	121	125	15	8	21	9
Change (d.f)	-5	-4	-4	-3	-6	-5
r ² (%)	11.6	12.5	87.3	96.7	85.6	85.1

Figures

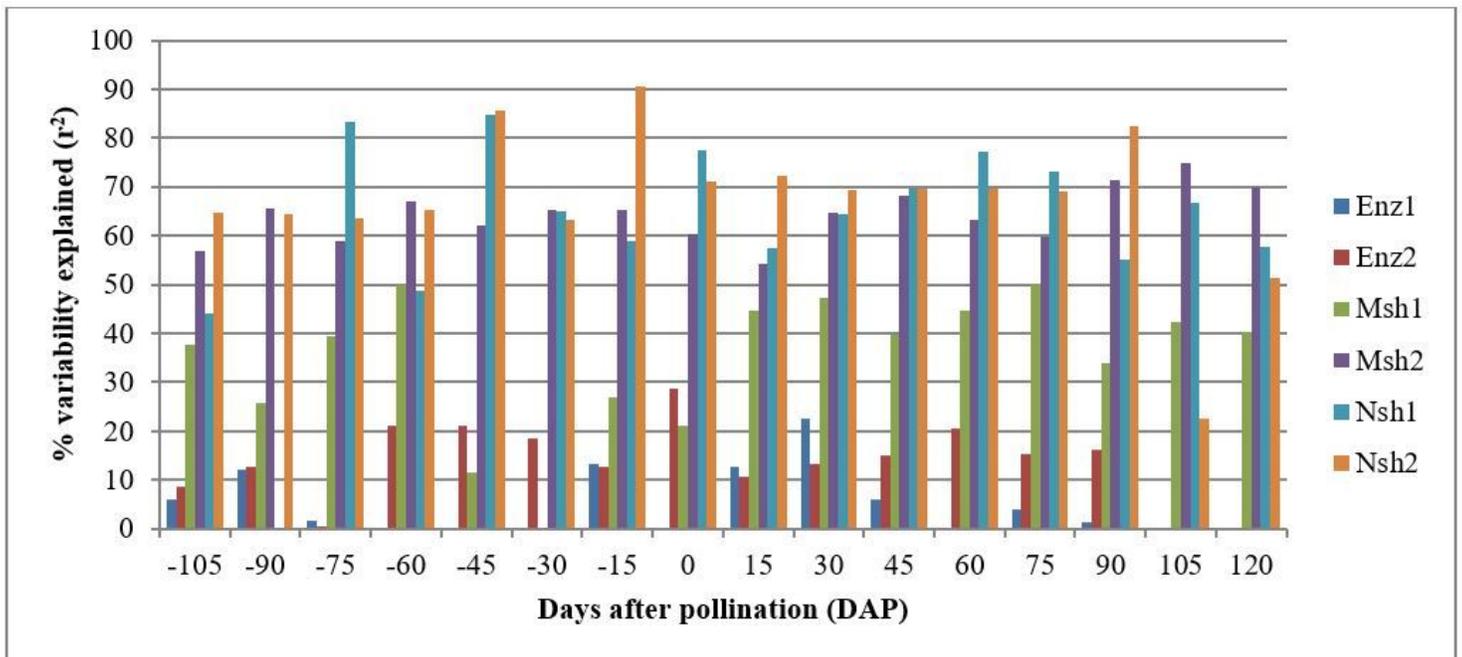


Figure 1

Percentage variability explained (r²) by the multiple linear model of seed set per 100 fruits as the dependent variable and weather attributes as independent variable at different development time intervals in 'Enzirabahima,' 'Mshale' and 'Nshonowa' after pollination with 'Calcutta 4' between January 2016 and January 2019 using two pollination techniques

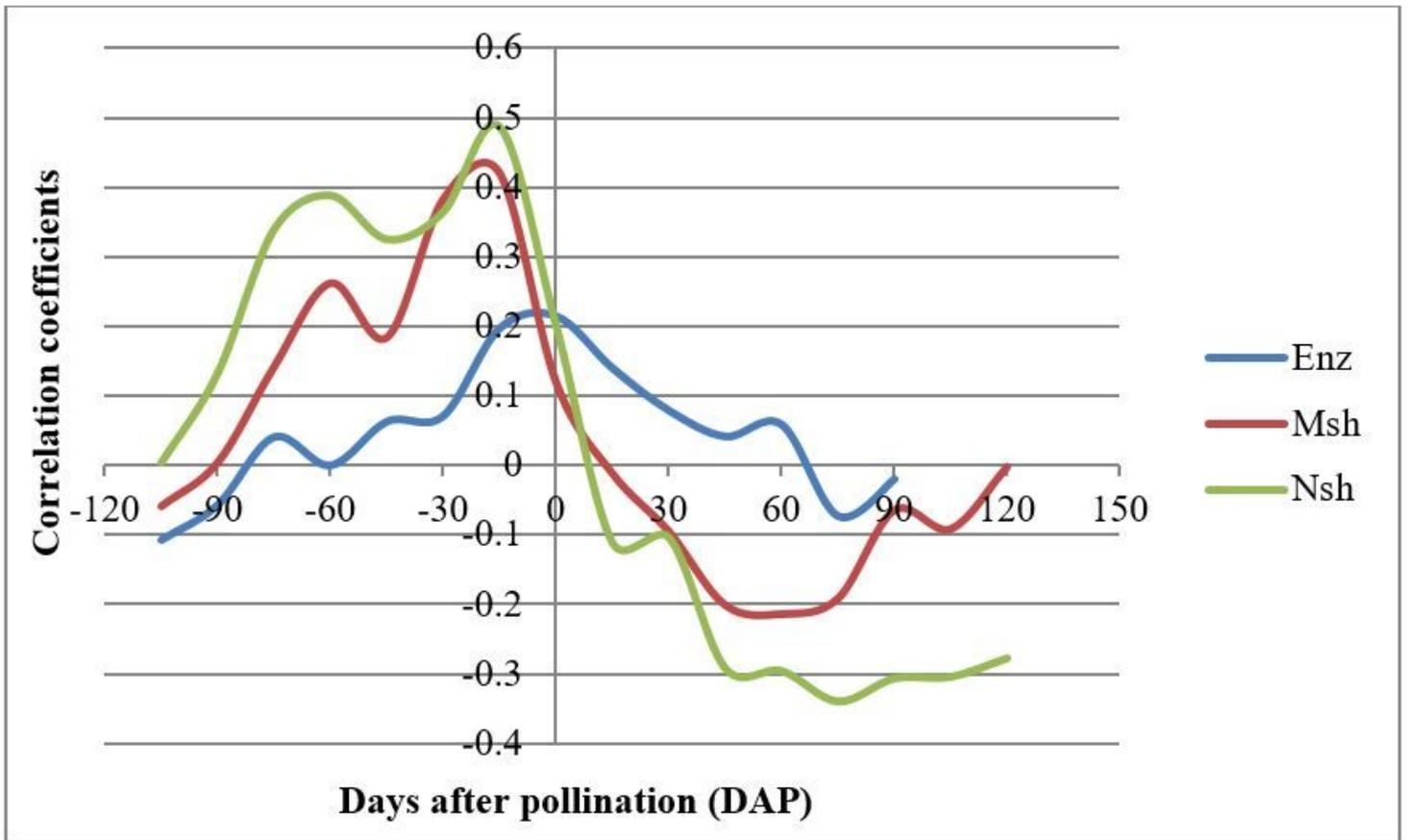


Figure 2

A graph of correlation coefficients between average temperature at 2 meter height and seed set per 100 fruits per bunch at various bunch development stages of 'Enzirabahima' (Enz), 'Mshale' (Msh), and 'Nshonowa'(Nsh) after pollination with PGM

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryTables27062020.docx](#)