Response of Sugarcane Cultivars to Chemical Ripeners During the Mid-Period of Harvesting in Ethiopia

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Abstract

The relatively high temperature at Kessem sugarcane plantation in Ethiopia was hypothesized to justify the implementation of chemical ripeners as a strategic intervention to combat poor cane quality. Accordingly, a field experiment was carried out to assess the responsiveness of four sugarcane varieties (B52-298, NCo334, C86-12, and SP70-1284) to five ripener treatments: 2-chloroethylphosphonic acid (Ethephon™, 480 g ai L^{-1}) at 720 g ai ha^{-1}, fluazifop-*p*-butyl (Fusilade Forte™, 150 g ai L^{-1}) at 25.6 g ai ha^{-1}, trinexapac-ethyl (Moddus™, 250 g ai L^{-1}) at 250 g ai ha^{-1}, 2-chloroethylphosphonic acid + fluazifop-*p*-butyl combination at the mentioned application rates, trinexapac-ethyl + fluazifop-*p*-butyl combination at the mentioned application rates, and an untreated control. The experiment was conducted in a factorial arrangement in a randomized complete block design (RCBD) with three replications. The results showed that stalk height, stalk weight, sucrose content (%), and sucrose yield (t ha^{-1}) were affected by the main effect of ripener treatment, but there was no significant cultivar x ripener treatment interaction for the parameters collected. Overall, the sequential application treatment of trinexapac-ethyl followed by fluazifop-*p*-butyl 28 days later performed the best and improved sucrose content and sucrose yield by 2.64% unit and 2.15 t ha^{-1}, respectively. In economic terms, the trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatment resulted in a marginal rate of return of 2393%. Therefore, the sequential trinexapac-ethyl + fluazifop-*p*-butyl ripener program was identified as a promising ripening strategy to be evaluated on a commercial scale at the sugarcane plantations in Ethiopia.

Keywords: Chemical ripening; 2-chloroethylphosphonic acid; Fluazifop-*p*-butyl; Trinexapac-ethyl; Sucrose yield

Introduction

Sugarcane (*Saccharum* spp. hybrid) is a major industrial crop in Ethiopia because of its broad socioeconomic value (Bharati et al. 2018), as well as the favorable climatic and edaphic conditions for its growth (EIA 2012). Sugarcane is generally cultivated for the production of sucrose, providing two-thirds of world sucrose supplies (Lakshmanan et al. 2005), and its sucrose yield (t ha^{-1}) is determined by the cane yield (t ha^{-1}) and sucrose content (%) of the stalk (Ebrahim et al. 1998; Sachdeva et al. 2011). Consequently, for a sugar mill to exist in the current competitive market, it is crucial to maximize the sucrose content and sucrose yield. As a strategic intervention, the Ethiopian Sugar Industry could employ sucrose per unit stalk mass boosting (ripening) mechanisms in areas where low stalk sucrose content is a prominent challenge (Ayele et al. 2016).

The sucrose content of sugarcane transported to the mill varies with the crushing period because ripening is influenced by many factors including soil fertility, irrigation, cultivars (van Heerden et al. 2014), weeds, pest and disease presence, and length of the crushing season (James 2004). Nevertheless, cool air temperature and water deficit are the main factors influencing ripening (Cardozo and Sentelhas 2013). Photosynthesis and respiration, which are the two major plant physiological processes, are affected by temperature (Yamori et al. 2005). The optimum temperature for growth and sucrose accumulation in the stalk has been described to be 27 °C (Ebrahim et al. 1998). The presence of adequate moisture for cane growth also reduces the sucrose content of sugarcane during ripening due to the high growth sink demand (Singels et al. 2000).

Conventionally, the Ethiopian sugarcane plantations employ drying-off by with-holding irrigation for a few weeks (5–9 weeks) before harvesting to facilitate cane burning, harvesting operations, and to improve stalk sucrose content (Getaneh and Negi 2014; Ayele et al. 2016). However, Gosnell and Lonsdale (1974) reported the inadequacy of this method for ripening. Effective drying-off requires accurate control over crop water supply (van Heerden et al. 2015), and there is risk of reduction in cane and sucrose yield due to excessive withholding of water (Robertson et al. 1999).

Consequently, the application of chemical ripeners was hypothesized to be the best strategy to improve competitive advantage and to resolve the low sucrose content problem at Kessem sugarcane plantation in Ethiopia. Many studies have indicated that chemical ripeners can provide appreciable increases in sucrose content above those attained by natural ripening (Resende et al. 2000; van Heerden et al. 2014). Successful use of chemical ripeners for the purpose of sugarcane ripening has already occurred in many industries (Eastwood and Davis 1997; Li and Solomon 2003). Reports from South Africa (van Heerden 2019), Swaziland (Rostron 1996), and Louisiana, the USA (Spaunhorst et al. 2019) indicated improved sucrose content and economic benefit from the use of chemical ripeners.

The ideal sugarcane ripener should increase sucrose yield in a rapid, persistent, consistent, and economic way, without damaging the crop, its following ratoon, or neighboring crops (Resende et al. 2000). It should also have low environmental toxicity and short half-life (Eastwood and Davis 1997). Since 1970, only a few chemicals emerged that fulfilled most or all of these criteria, and they have either herbicidal or hormonal modes of action. Among the ripeners which are in use currently are glyphosate (e.g., Roundup™), 2-chloroethylphosphonic acid (e.g., Ethephon™), fluazifop-*p*-butyl (e.g., Fusilade Forte™), and trinexapac-ethyl (e.g., Moddus™) (van Heerden et al. 2014).

Sugarcane cultivars differ from each other in their responses to chemical ripeners (Spaunhorst et al. 2019). In line with this, many reports confirmed the need for evaluation of sugarcane cultivars for their response to chemical ripeners (Kingston and Rixon 2007; Rixon et al. 2007). Thus, in every production environment, it is vital to evaluate existing sugarcane cultivars for their response to chemical ripeners. However, at Kessem sugarcane plantation, there is no information regarding the response of commercial sugarcane cultivars to chemical ripeners. Therefore, this study was undertaken to determine the effects of chemical ripeners on the yield and quality of sugarcane at this plantation.

Materials and Methods

Description of the Study Area

The experiment was conducted in the Central Rift Valley of Ethiopia at Kessem sugarcane plantation (39° 54′ E and 09° 09′ N) from March 2018 to January 2019. The plantation is located, at an elevation ranging from 750 to 850 m above sea level. The soil was classified as *Fluvisol* and silty clay in texture. Weather condition during the study period is presented in Fig. 1.

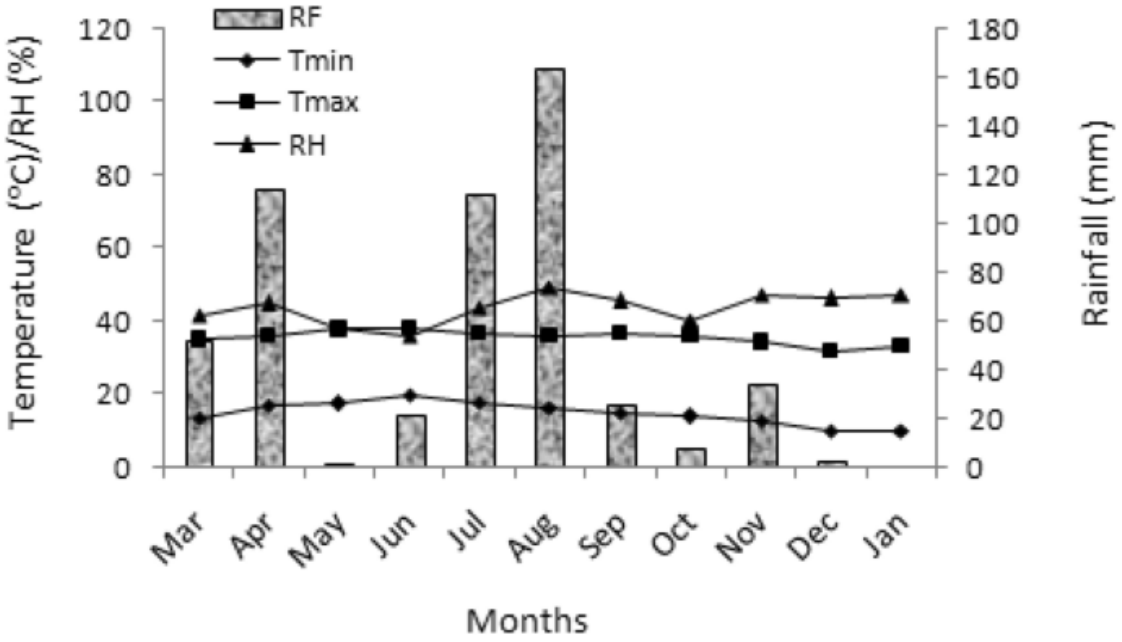

Fig. 1. Monthly total rainfall (RF) distribution, relative humidity (RH), the mean maximum (T_{max}) and minimum (T_{min}) temperature variations during the study period at Kessem Sugar Estate from March 2018 to January 2019

Treatments and Experimental Design

Four sugarcane cultivars and five ripener treatments, together with an untreated control, were used in the study. The three single application treatments were 2-chloroethylphosphonic acid (Ethephon™, 480 g ai L^{-1}) at 720 g ai ha^{-1}, fluazifop-*p*-butyl (Fusilade Forte™, 150 g ai L^{-1}) at 25.6 g ai ha^{-1}, and trinexapac-ethyl (Moddus™, 250 g ai L^{-1}) at 250 g ai ha^{-1}. The two sequential application treatments were 2-chloroethylphosphonic acid (Ethephon™, 480 g ai L^{-1}) at 720 g ai ha^{-1} + fluazifop-*p*-butyl (Fusilade Forte™, 150 g ai L^{-1}) at

25.6 g ai ha^{-1} and trinexapac-ethyl (Moddus™, 250 g ai L^{-1}) at 250 g ai ha^{-1} + fluazifop-*p*-butyl (Fusilade Forte™, 150 g ai L^{-1}) at 25.6 g ai ha^{-1}. Four sugarcane cultivars B52-298, NCo334, C86-12, and SP70-1284 were selected to be used as test crops. B52-298 and NCo334 were under cultivation at the plantation since the start of sugarcane processing in 2015. However, the cultivars C86-12 and SP70-1284 were selected based on their performance at Metehara sugar plantation. The experiment was conducted in a factorial arrangement in a randomized complete block design (RCBD) with three replications.

Field Management and Experimental Procedure

The experiment was conducted on a plant cane crop, and the study field was selected based on prior management histories to ensure the absence of any stress-inducing concerns such as water logging, irrigation inaccessibility, and other related issues. The crop was planted using three budded setts from eight-month-old stalk sourced from a seed cane nursery that was well-fertilized, irrigated, and disease-free. Throughout the growing season, irrigation was delivered in the furrows until two weeks before harvest. At two-and-a-half-month crop age, 200 kg ha^{-1} of urea (46% nitrogen) was applied manually. Weeding was conducted by hand as required. During the growth season, field inspections were undertaken on a regular basis, and no disease or insect pests were observed.

Water volumes of 431 L ha^{-1} were used to deliver the ripener spray mixes. Each plot consisted of 4 cane rows measuring 6 m long and 1.45 m row spacing with a total plot area of 34.8 m^2. Application of the ripeners was conducted using a high clearance boom frame with motorized knapsack sprayer operating at 100 kPa pressure at an average height of 0.5 m above the canopy of the crop. Spray mixtures were administered through two flood-jet nozzles, used to avoid chemical drift effects, spaced 0.5 m apart. Spraying of the ripeners was conducted early in the morning when the wind was calm. The age of harvesting was 10 months after planting, and the single treatments 2-chloroethylphosphonic acid, trinexapac-ethyl and fluazifop-*p*-butyl were applied 80, 70 and 42 days before harvest. For the sequential combination treatments, 2-chloroethylphosphonic acid was applied 80 days before harvest followed by fluazifop-*p*-butyl 42 days (6 weeks) ahead of harvest. Similarly, trinexapac-ethyl was applied 70 days before harvest followed by fluazifop-*p*-butyl 42 days prior to harvest.

Data Collected

At harvest, samples were taken from the two center cane rows in each plot. Stalk height was determined from twenty stalks per plot by measuring the length of stalks from the ground to top visible dewlap leaf. Millable stalk weight was determined from the combined twenty stalks per plot using a weighing balance. Cane yield was determined from the net plot area by weighing all the stalks using a weighing balance, and then, plot weights were converted to a hectare basis.

Brix (percent) was calculated using a ten stalk sample collected randomly from each plot. The stalks were crushed in a crushing mill, and the juice was analyzed using a bench refractometer (Rudolph Research, Model J157). A saccharimeter was used to determine Pol (%) from the same juice (Rudolph Research, Analytical Autopol 880). Purity (%) was calculated by multiplying the ratio of Pol (%) to Brix (%) by 100. Finally, the sucrose content (%) of cane was calculated as described by Berg (1972):

$$\text{Sucrose content } (\%) = [\text{pol } \% - (\text{Brix}\% - \text{pol}\%)\, 0.61]\, 0.75.$$

The non-sucrose factor is 0.61, while the crop factor is 0.75. The sucrose yield (t ha^{-1}) was calculated by multiplying the cane yield (t ha^{-1}) by the sucrose content (%) of the cane.

Data Analysis

To analyze the data, SAS version 9.2's PROC GLM procedure was employed (SAS 2009). The Tukey's Studentized Range (HSD) test was used to compare treatment means for the measured parameters at a 5% level of significance. The Kolmogorov–Smirnov test was used to determine whether the data distribution was normal.

The economic feasibility of the ripener treatments was determined utilizing CIMMYT's partial budget methodological approach (CIMMYT 1988). Only expenditures that differed across the ripener treatments were considered in the partial budget analysis. As a result, the partial budget did not include production costs, which were not relevant to the ripening treatment comparisons. Thus, the net benefit estimated per treatment does not equate to profit (income). The average experimental sucrose yield data were adjusted downwards by 10% to reflect the difference between the experimental plot sucrose yield and the sucrose yield that the plantation would expect under commercial condition (CIMMYT 1988).

The adjusted sucrose yield was multiplied by the sucrose selling price to calculate sales revenue. Then, for each treatment, the gross field benefit was computed by summing the savings from cane harvest and transportation, as well as sales revenue (income). The cost savings from cane harvest and transportation were the result of some chemical ripener treatments reducing cane yield. The cost of harvesting and transporting cane was set at USD 4.5 ha^{-1}. Chemical and spraying costs were combined to determine the ripening cost. Chemical ripener costs were USD 30.0, 23.0, and 33.3 ha^{-1}, respectively, for 2-chloroethylphosphonic acid, fluazifop-*p*-butyl, and trinexapac-ethyl, respectively. The cost of spraying (including labor) with a drone was estimated to be USD 5.62 ha^{-1}. Sucrose selling price was fixed at USD 0.62 kg^{-1}.

The net benefit (NB) was computed by deducting the total variable expenses (total cost of ripening) from the gross field benefit for each treatment. The marginal rate of return (MRR) was computed by dividing the difference between the treatment's net benefit and the control's net benefit by the variable cost of the treatment (cost of ripening). The MRR of a ripener treatment must be between 50 and 100% for it to be considered a viable choice for sugarcane plantation (CIMMYT 1988). For each treatment, residuals were produced to verify the marginal analysis results. The residuals were calculated using the difference between the net benefits achieved and the cost of investment.

Results and Discussion

Stalk Height and Weight

The analysis of variance indicated that stalk height and weight were influenced by the main effect of cultivar and ripener. However, there was no significant cultivar x ripener interaction (Table 1). Cultivar SP70-1284 had the tallest stalk (1.76 m), while there was no significant difference among NCo334, B52-298 and C86-12 (Table 2). The variation noted among the tested sugarcane cultivars might be due to their genetic differences (Habib et al. 1991). Abo El-Hamd et al. (2013) also reported the absence of cultivar × ripener interaction in stalk height.

Table 1 Analysis of variance (p values) for yield components and yield in a field experiment involving four sugarcane varieties and five chemical ripeners along with the control (unsprayed)

Source of variation	Stalk height (m)	Mean stalk weight (kg)	Cane yield (t ha^{-1})	Sucrose content (%)	Sucrose yield (t ha^{-1})
Variety (V)[a]	0.001	0.001	0.001	0.001	0.003
Ripener (R)[b]	0.001	0.001	0.311	0.001	0.007
Variety × ripener	0.831	0.994	0.978	0.550	0.781

[a]Cultivars: B52-298, NCo334, C86-12, and SP70-1284

[b]Ripener treatments: 2-chloroethylphosphonic acid, fluazifop-p-butyl, trinexapac-ethyl, 2-chloroethylphosphonic acid + fluazifop-p-butyl sequential application, trinexapac-ethyl + fluazifop-p-butyl sequential application, and control (unsprayed)

Table 2 Main effects of variety and ripener treatments on stalk height, stalk weight, stalk diameter, number of internodes, and number of millable stalks

Factor	Stalk height (m)	Stalk[a] weight (kg)	Cane yield (t ha^{-1})	Sucrose content (%)	Sucrose yield (t ha^{-1})
Cultivar					
B52-298	1.60 b	1.34 a	98.11 a	9.22 c	9.04 bc
NCo334	1.62 b	0.95 b	94.61 a	9.35 c	8.83 c
C86-12	1.55 b	1.34 a	84.84 b	11.69 a	9.92 ab
SP70-1284	1.76 a	1.31 a	94.92 a	10.78 b	10.19 a
Ripener					
2-chloroethylphosphonic acid (E)	1.74 ab	1.29 ab	95.26	9.92 b	9.39 ab
Fluazifop-*p*-butyl (FF)	1.56 c	1.18 c	89.99	10.42 b	9.34 ab
Trinexapac-ethyl (M)	1.57 c	1.22 bc	91.22	10.53 b	9.56 ab
E + FF	1.58 c	1.20 bc	92.11	10.52 b	9.67 ab
M + FF	1.59 bc	1.17 c	93.23	11.39 a	10.58 a
Control (unsprayed)	1.77 a	1.33 a	96.89	8.75 c	8.43 b
CV (%)	7.96	7.11	8.65	6.47	10.76

[a]Means were back-transformed for presentation. Means followed by the same letter or no letter in column are not significantly different from each other according to Tukey's HSD (0.05). Fluazifop-*p*-butyl was applied 38 days after 2-chloroethylphosphonic acid and 28 days after trinexapac-ethyl

In contrast, Orgeron (2012) reported the presence of cultivar × ripener interaction in stalk height.

In relation to the ripener treatments, the control (unsprayed) had the tallest stalks and was similar to the 2-chloroethylphosphonic acid treatment. In contrast, the other treatments all reduced stalk height when compared with the control. Stalk height was reduced by 12, 11, 11 and 10% by the fluazifop-*p*-butyl, trinexapac-ethyl, 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application, and trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatments, respectively (Table 2).

The production of ethylene by 2-chloroethylphosphonic acid diminishes the size and bulk of leaf canopy, which reduces the growth sink demand for sucrose (Eastwood and Davis 1997). The findings of the current study are consistent with prior research which found that 2-chloroethylphosphonic acid did not reduce sugarcane stalk height (Rostron 1985; van Heerden et al. 2015). A decline in stalk growth due to the shortening of one or two internodes may occur, although it has been shown to be transient (Rostron 1985). On the other hand, treatment with 2-chloroethylphosphonic acid resulted in a significant drop in stalk height (Abo El-Hamd et al. 2013).

The reduction in stalk height due to fluazifop-*p*-butyl treatment resulted from the transfer of the active ingredient to the stalk apical meristem where it terminates stalk growth (Eastwood and Davis 1997; Rostron 1985) and limits the growth of leaves (Rostron 1985). According to Abo El-Hamd et al. (2013), fluazifop-*p*-butyl treatment reduced stalk height regardless of application rates. The effects of fluazifop-*p*-butyl, when used at ripener application rates, are slow-acting and do not interfere with photosynthesis directly, allowing sucrose accumulation to continue even after stalk growth stops (Petrasovits et al. 2013).

Similarly, the reduction in stalk height caused by trinexapac-ethyl treatment was the result of reduced internode elongation caused by an inhibition of the gibberellic acid GA_{20} to GA_1 conversion pathway within the sugarcane stalk (Resende et al. 2000; Rixon et al. 2007; van Heerden et al. 2015). Similarly, Orgeron (2012) found that a 350 g ai ha^{-1} application rate of trinexapac-ethyl resulted in a considerable reduction in stalk height. Trinexapac-ethyl at rates of 200, 250, and 500 g ai ha^{-1} resulted in a quick and near-complete restriction of stalk growth up to 56 days following its application (van Heerden et al. 2015). The application rate, on the other hand, determined subsequent re-growth.

Compared to the control treatment, the sequential application of 2-chloroethylphosphonic acid + fluazifop-*p*-butyl and trinexapac-ethyl + fluazifop-*p*-butyl both reduced stalk height, albeit their effects were not different (Table 2). Due to the differential effect of the separate ripeners on stalk height (Sweet et al. 1987), the reduction in stalk height from the 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application treatment was mostly caused by fluazifop-*p*-butyl due to cessation of the stalk apical meristem (Eastwood and Davis 1997).

A reduction in stalk height from the sequential application of 2-chloroethylphosphonic acid and fluazifop-*p*-butyl was also reported by Abo El-Hamd et al. (2013). In a similar manner, the reduction in stalk height from the trinexapac-ethyl + fluazifop-*p*-butyl sequential application was due to the synergistic effect of both ripeners on stalk elongation (Eastwood and Davis 1997; Resende et al. 2000; van Heerden et al. 2015).

The cultivar NCo334 had the lowest stalk weight (0.95 kg) (Table 2). The difference among the tested sugarcane cultivars might be due to their innate genetic differences. Similarly, Orgeron (2012) also reported differences in stalk weight among sugarcane cultivars.

Stalk weight in the control treatment was similar to 2-chloroethylphosphonic acid treatment. Stalk weight in the 2-chloroethylphosphonic acid treatment, in turn, was greater than stalk weights in the fluazifop-*p*-butyl and sequential application of trinexapac-ethyl + fluazifop-*p*-butyl treatments (Table 2). However, stalk weight in the 2-chloroethylphosphonic acid treatment was not significantly different from the trinexapac-ethyl and the sequential application of 2-chloroethylphosphonic acid + fluazifop-*p*-butyl (Table 2).

It is important to highlight the fact that the lack of influence of 2-chloroethylphosphonic acid on stalk weight was a reflection of its lack of influence on stalk length. The same holds true for the significant reduction in stalk weight in the fluazifop-*p*-butyl, trinexapac-ethyl, 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application and trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatments. This is explained by the fact that stalk elongation is positively correlated with stalk weight (Silva et al. 2008).

Cane Yield, Sucrose Content and Sucrose Yield

Cane yield was affected only by the main effect of cultivar (Table 1). The highest cane yield (98.11 t ha^{-1}) was recorded in cultivar B52-298, which was similar to the cane yields in cultivars NCo334 and SP70-1284, while cultivar C86-12 had lowest cane yield (84.84 t ha^{-1}) (Table 2). The difference between the tested cultivars in cane yield might be attributed to their genetic makeup (Abo El-Hamd et al. 2013).

Although all the chemical ripener treatments, except for 2-chloroethylphosphonic acid, reduced stalk height and weight although this did not translate into reductions in cane yield. The lack of significant effects on cane yield among the ripener treatments could be due to increase in stalk mass (effective ripening), as evidenced by the increase in sucrose content induced by the various ripener treatments, as well as the study's relatively short spray-to-harvest intervals (van Heerden 2013) and lower chemical rates (Abo El-Hamd et al. 2013).

Similarly, other authors also reported the absence of significant cane yield reduction due to treatment with fluazifop-*p*-butyl (van Heerden 2013) and trinexapac-ethyl (Kingston and Rixon 2007; Resende et al. 2000). Contrary to this, Abo El-Hamd et al. (2013) reported a significant cane yield reduction due to treatment with fluazifop-*p*-butyl. Similarly, Orgeron (2012) reported a significant reduction of cane yield due to treatment with trinexapac-ethyl applied at 300 and 350 g ai ha^{-1}.

Sucrose content (%) was affected only by the main effects of cultivar and ripener (Table 1). Cultivar C86-12 had the highest sucrose content (11.69%) followed by SP70-1284, which in turn had higher sucrose content than NCo334 and B52-298 (Table 2).

The trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatment resulted in the highest sucrose content of all treatments, whereas the control had the lowest sucrose content (Table 2). Compared to the control treatment, the sucrose content due to the application of 2-chloroethylphosphonic acid, fluazifop-*p*-butyl, trinexapac-ethyl, 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application and trinexapac-ethyl + fluazifop-*p*-butyl

sequential application increased by 1.18, 1.68, 1.79, 1.78 and 2.65% units, respectively (Table 2).

The increase in sucrose content in the ripener treatments was due to the reduced growth sink demand, which ultimately led to the accelerated accumulation of sucrose in the stalk (Resende et al. 2000; Rixon et al. 2007). Similar to this study, earlier research also confirmed increase in sucrose content due to treatment with 2-chloroethylphosphonic acid (Abo El-Hamd et al. 2013), fluazifop-*p*-butyl (Abo El-Hamd et al. 2013; van Heerden 2019) and trinexapac-ethyl (Kingston and Rixon 2007; Resende et al. 2000). Similarly, other studies also reported the synergistic and additive effect of 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application (Rostron 1985; Sweet et al. 1987) and trinexapac-ethyl + fluazifop-*p*-butyl sequential application (van Heerden 2013) in increasing sucrose content.

Analogous to sucrose content, sucrose yield (t ha^{-1}) was also significantly influenced by the main effects of cultivar and ripener (Table 1). Among the cultivars, SP70-1284 had the highest sucrose yield (10.19 t ha^{-1}), which was similar to C86-12; however, NCo334 recorded the lowest sucrose yield (Table 2). Among the ripener treatments, trinexapac-ethyl + fluazifop-*p*-butyl sequential application resulted in the highest sucrose yield (10.58 t ha^{-1}) and was the only treatment that differed significantly from the control (Table 2).

The large increase in sucrose content that exceeded all other treatments and the lack of any negative effect on cane yield explains the very large positive sucrose yield response achieved from the sequential application of trinexapac-ethyl + fluazifop-*p*-butyl. Consistent with the current finding, van Heerden (2013) also reported the synergistic effect of trinexapac-ethyl + fluazifop-*p*-butyl sequential application in increasing sucrose yield.

Economic Analysis

The trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatment yielded the highest net benefit of USD 5839.93 ha^{-1} followed by the 2-chloroethylphosphonic acid + fluazifop-*p*-butyl sequential application treatment (USD 5328.24 ha^{-1}), trinexapac-ethyl (USD 5292.42 ha^{-1}), fluazifop-*p*-butyl (USD 5205.26 ha^{-1}), 2-chloroethylphosphonic acid (USD 5168.22 ha^{-1}), and control (USD 4678.71 ha^{-1}) treatments, respectively (Table 3).

Regarding the marginal rate of return, the highest value of 5509% was obtained from the sole treatment fluazifop-*p*-butyl, while the lowest was obtained from the sole 2-chloroethylphosphonic acid treatment (967%). This variation in marginal return value was due to the lower cost of ripening in the sole treatment fluazifop-*p*-butyl (Table 3).

However, in marginal analysis, the marginal rate of return is not the final criterion for recommendation since it does not account for the returns on investment (residuals). The maximum return on investment was obtained from the trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatment (USD 5791.41 ha^{-1}). Therefore, the most economical option among the ripener treatments was derived from the trinexapac-ethyl + fluazifop-*p*-butyl sequential application with a marginal rate of return of 2393% (Table 3). In all the ripener treatments, a marginal rate of return greater than 1 was obtained compared to the control (unsprayed) (Table 3), which is greater than the minimum requirement.

Table 3 Partial budget analysis for sucrose yield from the five ripener treatments for the experiment conducted at Kessem sugar estate

Parameters	Ripener treatments					
	Control	2-Chloroethyl-phosphonic acid	Fluazifop-*p*-butyl	Trinexapac-ethyl	E + FF	M + FF
Actual sucrose yield (kg ha^{-1})	8430.0	9390.0	9340.0	9560.0	9670.0	10,580.0
Adjusted sucrose yield (kg ha^{-1})	7587.0	8451.0	8406.0	8604.0	8703.0	9522.0
Sales revenue from sucrose (USD ha^{-1})	4678.7	5211.5	5183.8	5305.9	5366.9	5872.0
Saving from HT (USD ha^{-1})[a]	0.0	7.3	31.0	25.5	21.5	16.5
Gross field benefit (USD ha^{-1})	4678.7	5218.8	5214.8	5331.4	5388.4	5888.4
Cost of chemicals (USD ha^{-1})	0.0	45.0	3.9	33.3	48.9	37.3
Cost of spraying (USD ha^{-1})	0.0	5.6	5.6	5.6	11.25	11.2
Cost of ripening (costs that vary) (USD ha^{-1})	0.0	50.6	9.6	38.9	60.2	48.5
Net benefit (USD ha^{-1})	4678.7	5168.2	5205.3	5292.4	5328.2	5839.9
Marginal rate of return (%)	–	967	5509	1575	1079	2393
Return on investment (residuals) (USD ha^{-1})	4678.7	5117.6	5195.7	5253.5	5268.1	5791.4

E denotes 2-chloroethylphosphonic acid, FF denotes fluazifop-*p*-butyl, M denotes trinexapac-ethyl

[a]HT = harvest and transport

Conclusions

The results presented in this study clearly showed the high level of effectiveness of chemical ripeners in increasing sucrose content and sucrose yield at Kessem sugarcane plantation. Overall, ripeners consistently increased sucrose yield. All the studied sugarcane cultivars responded positively, with sucrose content increases of more than 1% unit compared to the control treatment in all the ripener treatments. However, the trinexapac-ethyl + fluazifop-*p*-butyl sequential application was found to be the best ripener treatment to increase sucrose yield of sugarcane cultivars B52-298, NCo334, C86-12 and SP70-1284. Furthermore, in economic terms, the trinexapac-ethyl + fluazifop-*p*-butyl sequential application treatment was found to be the best option. Therefore, it is advisable to evaluate these experimental results at a commercial level during the mid-period of sugarcane crushing on immature crops cultivated at sugarcane plantations in Ethiopia.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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