Research Article

Ripening Response of Sugarcane Varieties to Chemical Ripeners and Economic Benefits during the Early Period of Harvesting at Wonji-Shoa and Metahara Sugarcane Plantations, Central Rift Valley of Ethiopia

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Wonji-Shoa and Metahara sugarcane plantations experience reduced sucrose content (%) during the starting period of sugarcane crushing due to the combined influence of high (>27°C) temperature and the presence of high residual soil moisture. Studies elsewhere showed the potential of chemical ripeners in boosting the sucrose content (%), where natural ripening is deterred by these challenges. Accordingly, a field experiment was conducted to evaluate the responsiveness of selected sugarcane varieties to chemical ripeners at both plantations. The treatments consisted of a factorial combination of four sugarcane varieties (B52-298, NCo334, C86-56, and SP70-1284) and six ripener treatments: (1) Ethephon™ (720 g a.i. ha⁻¹), (2) Fusilade Forte™ (25.6 g a.i. ha⁻¹), (3) Moddus™ (250 g a.i. ha⁻¹), (4) Ethephon™ (720 g a.i. ha⁻¹) + Fusilade Forte™ (25.6 g a.i. ha⁻¹), (5) Moddus™ (250 g a.i. ha⁻¹) + Fusilade Forte™ (25.6 g a.i. ha⁻¹), and (6) Unsprayed (control). The experiment was laid out in a randomised complete block design in a factorial arrangement with three replications. The results showed a significant (p ≤ 0.025) and highly significant (p ≤ 0.001) variety by ripener interaction in stalk height and sucrose content, respectively, while the main effect ripener highly significantly affected stalk weight (p ≤ 0.001) and sucrose yield (p ≤ 0.003). The variety C86-56 sprayed with combinations of Ethephon™ + Fusilade Forte™ and Moddus™ + Fusilade Forte™ had the shortest stalk heights of 1.27 and 1.29 m, respectively, compared with the control. Ethephon™ + Fusilade Forte™ combination resulted in the highest reduction of stalk weight (8.36%), while the lowest was recorded in the sole Moddus™ treatment (6.31%). From the ripener treatments, the Moddus™ + Fusilade Forte™ combination improved sucrose yield by 1.42 and 1.34 t ha⁻¹, respectively, compared with the control. However, in economic terms, the Moddus™ + Fusilade Forte™ combination treatment resulted in the highest marginal rate of return of 1244%. Therefore, the Moddus™ + Fusilade Forte™ combination ripener treatment was found to be promising to be evaluated at a commercial scale on immature sugarcane varieties B52-298, NCo334, and SP70-1284.

1. Introduction

Sugarcane (Saccharum spp., hybrid) is cultivated in Ethiopia at a commercial level [1], as well as by smallholder farmers [2]. It also has broad socioeconomic advantages [3]. However, the per-capita sugar consumption of Ethiopia is one of the lowest in the world with about 5 to 6 kg per annum, and future sugar consumption growth is expected to be around 3–4% annually, which was forecasted to grow by 0.4 million tons by 2030 [4]. The total annual sugar production in the country was reported to be 400,000 tons in 2018, which only covers 60% of the annual demand for...
domestic consumption [5]. The country is endowed with a favourable climate, enormous land, and water resources for large-scale irrigated development of sugarcane [1] with an average sugarcane yield potential of 162 tons per hectare [6]. Nonetheless, the value of sugarcane is determined by the amount of recoverable sucrose per weight of cane [7]. In Ethiopia, sucrose is the main product of sugarcane processing [8], and its quantity principally depends on the quality of sugarcane supplied [9]. This suggests the need for maintaining quality using appropriate ripening management as an indispensable means [10].

Although the dry matter yield potential of sugarcane in the country is high [6], the quantity partitioned to sucrose varies depending upon the variety, age [11], season [8], soil fertility, irrigation [12], weed, pest and disease control [13], and the length of crushing season [7]. Nevertheless, air temperature and soil moisture are the major factors affecting the partitioning of sucrose in sugarcane [14]. At a higher temperature, from the total carbon fixed and stored, sugarcane partitions less carbon to sucrose [15]. The availability of soil moisture also reduces the sucrose content of sugarcane during ripening due to the high growth sink demand [16]. In the ripening phase, there should be a synthesis and rapid accumulation of sucrose with a concomitant reduction of vegetative growth and a decline in the level of monosaccharides (fructose and glucose) in stalks [12].

Wonji-Shoa and Metahara sugarcane plantations have a total area of 10,342 and 10,235 ha, respectively. Conventionally, to maximise the sucrose content (% of cane harvested from these plantation areas, harvesting of sugarcane is conducted after drying off the cane by withholding irrigation for a specified period ranging from 5 to 9 weeks before harvesting [17]. However, the sucrose content of cane in the beginning (September to November) period is lower due to the presence of residual soil moisture coupled with the high temperature in July and August, and this has been reported to be a persistent problem at both estates [8]. This indicates the inadequacy of natural ripening [18], which resulted in the need for accurate control over crop water supply [19] and the reduction in cane and sucrose yield from the extreme withholding of water during drier periods [20].

Chemical ripeners have become an important technology to tackle challenges related to low sucrose content in many sugar industries of the world [12]. Ripeners used in sugarcane are plant regulators whose action consists of modification of plant morphology and physiology, which can alter plant production quantitatively and qualitatively [21]. The use of ripeners can provide gains in sucrose quality above those achieved by natural ripening [12, 19]. Ripeners can reduce plant height, increase sucrose content, advance plant maturation, and increase sucrose yield, and they can also present effects on enzymes that catalyse sucrose accumulation in the internodes [21]. The technology has potentially considerable impact in areas overwhelmed with poor natural ripening conditions [22]. The successful introduction of ripener technology could also facilitate the harvest of cane earlier in the season when it is relatively immature [23].

The chemical ripeners currently in use in many sugar industries include glyphosate (e.g., Roundup™), 2-chloroethylphosphonic acid (e.g., Ethephon™), fluazifop-p-butyl (e.g., Fusilade Forte™), and trinexapac-ethyl (Moddus™) [12]. In terms of their modes of action, glyphosate and fluazifop-p-butyl are herbicidal and suppress new tissue formation at a sublethal dose [24], while 2-chloroethylphosphonic acid and trinexapac-ethyl have a hormonal mode of action [25, 26]. The hormonal mechanism of improvement in sucrose content through 2-chloroethylphosphonic acid emanates from the active ingredient ethylene [25, 26], which reduces the demand for sucrose for vegetative growth [24]; but the mechanism for trinexapac-ethyl is related to its ability of inhibition of elongation of internode, resulting from the reduction in the level of GA$_1$ [27]. Earlier works also confirmed the efficacy of sole application of glyphosate [24, 28], 2-chloroethylphosphonic acid [29, 30], fluazifop-p-butyl [30, 31], trinexapac-ethyl [32, 33], and combination of ripeners [23, 29, 30] in improving sucrose yield of sugarcane.

However, to effectively use chemical ripeners at a commercial level, it is vital to generate information regarding the response of sugarcane varieties to these chemicals. In line with this study, reports from different sugar industries confirmed the need for evaluation of varieties for their response to chemical ripeners [23, 28]. In this regard, a preliminary study conducted at Metahara sugarcane plantation in the 1980s using fluazifop-p butyl showed that the sucrose content (%) of varieties B4I-227 and NCO376 were improved by 0.47 and 0.57% units, respectively, when compared with untreated control plots [29].

Although these studies showed improvement in juice quality of some sugarcane varieties, the emergence of new chemical ripeners, combination treatments, and sugarcane varieties necessitated another study that can provide up-to-date information to the estates. Therefore, this study was conducted to evaluate the response of selected sugarcane varieties to chemical ripeners at Wonji-Shoa and Metahara sugarcane plantations.

2. Materials and Methods

2.1. Description of the Study Areas. The present investigation was carried out at Wonji-Shoa and Metahara sugarcane plantations from December 2017 to October 2018. Wonji-Shoa Sugarcane plantation is located in the Rift Valley of Ethiopia (8°31’N and 39°12’E), at an average elevation of 1550 masl. The plantation has a mean maximum and minimum air temperature of 26.9 and 15.3°C, respectively. Similarly, Metahara sugarcane plantation is located in the Rift Valley of Ethiopia (8°51’N and 39°52’E), at an average elevation of 950 masl. The plantation has a mean maximum and minimum air temperature of 32.6 and 17.5°C, respectively. The soils of the experimental fields of Wonji-Shoa and Metahara were clay (>54%) in texture.

During the study period, Wonji-Shoa and Metahara sugarcane plantations obtained a total rainfall of 859 and 317 mm, respectively. As compared to the long-term annual average, both plantations experienced lower rainfall. Moreover, the distribution was not even at both locations (Figure 1). Maximum rainfall of 267 and 120 mm were
2.2. Description of the Experimental Materials. Two existing sugarcane varieties (B52-298 and NCo334), which have been in cultivation for more than five decades at Wonji-Shoa and Metahara sugarcane plantations, and two new varieties (C86-56 and SP70-1284) recently introduced from Cuba were selected based on their performance at both locations. The chemical ripeners used for the study were 2-chloroethylphosphonic acid (Ethephon™), fluazifop-p-butyl (Fusilade Forte™), and trinexapac-ethyl (Moddus™). The formulations were 480, 150, and 250 g ai L⁻¹ (gram active ingredient per litre) for Ethephon™, Fusilade Forte™, and Moddus™, respectively.

2.3. Treatment and Experimental Design. The treatments consisted of a factorial combination of four sugarcane varieties (B52-298, NCo334, C86-56, and SP70-1284) and six ripener treatments: (1) Ethephon™ (720 g ai ha⁻¹), (2) Fusilade Forte™ (25.6 g ai ha⁻¹), (3) Moddus™ (250 g ai ha⁻¹), (4) Ethephon™ (720 g ai ha⁻¹) + Fusilade Forte™ (25.6 g ai ha⁻¹), (5) Moddus™ (250 g ai ha⁻¹) + Fusilade Forte™ (25.6 g ai ha⁻¹), and (6) Control (unsprayed). The experiment was conducted using a randomised complete block design in a factorial arrangement with three replications.

2.4. Experimental Procedure. The experiment was planted using three budded sets originated from properly managed seed source fields. Throughout the growing period, furrow irrigation was provided until two weeks before harvesting. Urea (46% N) was applied once at 200 kg ha⁻¹ manually after a mechanical earthing-up operation was conducted at two and a half months of cane age. Weeding was conducted manually as required. Irrigation and weeding were conducted similar to commercial practice on the estates. Field inspections were conducted every 15 days, and there were no diseases and insect pests encountered throughout the growing period.

Each plot had 4 cane rows of 6 meters long and 1.45 m row spacing with a total plot size of 34.8 m². Samples were collected from the centre 2 rows. Applications of the ripeners were conducted using a high-clearance boom frame using a motorised power sprayer operating at 100 kPa pressure at an average height of 50 cm above the canopy with two flood-jet nozzles, used to reduce chemical drift effects, spaced at 50 cm apart. The spray mixtures were delivered in water volumes of 431 L ha⁻¹. Spraying was conducted early in the morning when the wind was calm.

The age of harvesting was 10 months at both locations. Ethephon™, Moddus™, and Fusilade Forte™ were applied 80, 70, and 42 days prior to harvesting. For the combination treatment Ethephon™ + Fusilade Forte™, Ethephon™ was applied 80 days before harvest followed by Fusilade Forte™ 42 days before harvesting. Similarly, for the Moddus™ + Fusilade Forte™ combination treatment, Moddus™ was applied 70 days before harvesting followed by Fusilade Forte™, which was sprayed 42 days before harvesting.

2.5. Data Collection. At harvest, millable stalk height and stalk weight were calculated from 20 stalks, while 10 stalks were used for juice quality viz. Brix (%) and Pol (%) measurements. The stalks were randomly selected from the net plot. Millable stalk height was determined by measuring the height of stalks from the ground to the top visible dewlap leaf. Stalk weight was determined using a weighing balance. The number of millable stalks was counted before sampling and harvesting. Cane yield was determined from the net plot area by weighing all stalks using a weighing balance and then converted to tons per hectare.

Brix (%) was determined by crushing the stalks using a crushing mill, and the juice was analysed in the laboratory using a bench refractometer (Rudolph Research, model J157). Similarly, pol (%) was determined from the same juice using a saccharimeter (Analytical Autopol 880; Rudolph...
3. Results and Discussion

3.1. Sugarcane Yield Components

3.1.1. Stalk Height. The combined analysis over the two locations showed a significant \((p = 0.025)\) interaction effect of ripener with variety on stalk height. However, none of the remaining interactions with ripeners were significant (Table 1).

The variety C86-56 treated with combinations of Ethephon™+ Fusilade Forte™ and Moddus™+ Fusilade Forte™ had the shortest stalk heights of 1.27 and 1.29 m, respectively. In contrast, the longest stalk height (1.64 m) was recorded in the control (unsprayed) treatment of variety NCo334 (Figure 2). The difference in response among the varieties to chemical ripeners might have been due to their innate genetic differences. In line with this, reports from different sugar industries confirmed the difference in response to chemical ripeners [27, 33].

Physiologically, 2-chloroethylyphosphonic acid reduces the growth sink demand for sucrose due to the reduction in the lamina size and mass as a result of the release of ethylene [24]. The current research results agree well with previous studies wherein 2-chloroethyl-phosphonic acid did not cause significant stalk height reduction in sugarcane [19, 27]. According to Rostron [34], a reduction in stalk growth by shortening of one or two internodes may occur, but it was confirmed to be transitory. Contrarily, Abo El-Hamd et al. [35] showed a significant reduction in stalk height due to 2-chloroethylphosphonic acid treatment. The reduction in stalk height due to Fusilade Forte™ treatment was caused by the translocation of the active compound fluazifop-p-buty1 to the stalk apical meristem where it terminates stalk growth [24, 34] and restricts leaf growth [34]. Abo El-Hamd et al. [35] also reported that fluazifop-p-buty1 treatments reduced stalk height independent of the rates considered.

In the same way, the reduction in stalk height due to the treatment with Moddus™ was caused by the reduction of internode elongation, which resulted from the blockage of gibberellic acid \(\text{GA}_20\) to \(\text{GA}_3\) conversion process within the sugarcane stalk [19, 27]. Similarly, van Heerden et al. [19] revealed that trinexapac-ethyl applied at the rate of 200, 250, and 500 g ai ha\(^{-1}\) caused a rapid, and near-complete, inhibition of stalk growth up to 56 days after spraying. However, subsequent resumption of growth depended on the application rate.

The stalk height reduction due to treatment with the Ethephon™+ Fusilade Forte™ combination treatment (Figure 2) predominately originated from fluazifop-p-buty1 contained in Fusilade Forte™ [24, 34]. On the other hand, the reduction in stalk height due to treatment with the Moddus™+ Fusilade Forte™ combination (Figure 2) could be due to the reduction in stalk elongation from the synergistic effect of both the active ingredients fluazifop-p-buty1 and trinexapac-ethyl [19, 24].

3.1.2. Stalk Weight. The ripener main effect on stalk weight (Table 1) was highly significant \((p = 0.001)\). Fusilade Forte™, Moddus™, Moddus™+ Fusilade Forte™ combination, and Ethephon™+ Fusilade Forte™ combination treatments significantly reduced stalk weight (Figure 3), although actual
Table 1: Combined analysis of variance (p values) for yield components of sugarcane in a field experiment involving four sugarcane varieties, six chemical ripener treatments, and two locations.

| Source of variation | Stalk height (m) | Stalk weight (kg stalk−1) | No. of millable stalks (‘000/ha) |
|---------------------|------------------|--------------------------|-----------------------------|
| Variety (V)1         | 0.001            | 0.001                    | 0.001                       |
| Ripener (R)2         | 0.001            | 0.001                    | 0.970                       |
| Location (L)3        | 0.168            | 0.002                    | 0.017                       |
| V × R                | 0.025            | 0.966                    | 0.649                       |
| R × L                | 0.653            | 0.802                    | 0.891                       |
| V × R × L            | 0.919            | 0.939                    | 0.562                       |

1Varieties: B52-298, NCo334, C86-56, and SP70-1284; 2Ripener treatments: Ethephon™, Fusilade Forte™, Moddus™, Moddus™ + Fusilade Forte™ combination, Ethephon™ + Fusilade Forte™ combination, and control (unsprayed). 3Locations: Wonji-Shoa and Metahara.

Figure 2: Difference in stalk height among sugarcane varieties for the ripeners Ethephon™ (E), Fusilade Forte™ (FF), Moddus™ (M), Moddus™ + Fusilade Forte™ combination (M + FF), and Ethephon™ + Fusilade Forte™ combination (E + FF) treatments. Mean values followed by the same letter are not significantly different according to HSD0.05. The bars indicate the mean standard deviations of six observations.

Figure 3: The effects of ripeners Ethephon™ (E), Fusilade Forte™ (FF), Moddus™ (M), Moddus™ + Fusilade Forte™ combination (M + FF), and Ethephon™ + Fusilade Forte™ combination (E + FF) treatments on stalk weight and number of millable canes. Mean values followed by the same letter are not significantly different according to HSD0.05. The bars indicate the mean standard deviations of twenty-four observations.

Figure 4: Difference in sucrose content among sugarcane varieties B52-298, NCo334, C86-56, and SP70-1284 for the ripeners Ethephon™ (E), Fusilade Forte™ (FF), Moddus™ (M), Moddus™ + Fusilade Forte™ combination (M + FF), and Ethephon™ + Fusilade Forte™ combination (E + FF) treatments. Mean values followed by the same letter are not significantly different according to HSD0.05. The bars indicate the mean standard deviations of six observations.

3.2. Cane Yield, Sucrose Content, and Sucrose Yield

3.2.1. Cane Yield. The ripener treatments did not result in a significant reduction in cane yield (Table 2 and Figure 5). Therefore, cane yield did not reflect the observations of ripener treatment effects on stalk height and weight (Figures 2 and 3). The absence of significant effects on cane yield among the ripener treatments might have been due to effective ripening (increase in sucrose mass per stalk), as et al. [35] reported a significant reduction in stalk population due to 2-chloroethylphosphonic acid applied at a higher rate (1143 g ai ha−1). Likewise, Abo El-Hamd et al. [35] also demonstrated that fluazifop-p-butyl at a higher rate (88.3 g ai ha−1) had resulted in a significant reduction in stalk population. The combination of 2-chloroethylphosphonic acid (1143 g ai ha−1) + fluazifop-p-butyl (88 g ai ha−1) also reduced stalk population [35].

3.1.3. Number of Millable Stalks. The number of millable stalks (stalk population) was not significantly affected by the ripener main effect as well as by its interactions (Tables 1 and Figure 3). Similar to the current result, Lu et al. [36] also demonstrated the negligible effect of 2-chloroethylphosphonic acid on stalk population. In contrast, Abo El-Hamd et al. [35] reported a significant reduction in stalk population due to 2-chloroethylphosphonic acid applied at a higher rate (1143 g ai ha−1). Likewise, Abo El-Hamd et al. [35] also demonstrated that fluazifop-p-butyl at a higher rate (88.3 g ai ha−1) had resulted in a significant reduction in stalk population. The combination of 2-chloroethylphosphonic acid (1143 g ai ha−1) + fluazifop-p-butyl (88 g ai ha−1) also reduced stalk population [35].
Table 2: Combined analysis of variance (p values) for cane yield, sucrose content, and sucrose yield in a field experiment involving four sugarcane varieties, six chemical ripener treatments, and two locations.

| Source of variation | Cane yield (t/ha) | Sucrose content (%) | Sucrose yield (t/ha) |
|---------------------|-------------------|---------------------|---------------------|
| Variety (V)         | 0.001             | 0.003               | 0.001               |
| Ripener (R)         | 0.201             | 0.001               | 0.003               |
| Location (L)        | 0.064             | 0.102               | 0.172               |
| V × R               | 0.956             | 0.001               | 0.100               |
| R × L               | 0.733             | 0.295               | 0.757               |
| V × R × L           | 0.995             | 0.999               | 0.998               |

1Varieties: B52-298, NCo334, C86-56, and SP70-1284. 2Ripener treatments: Ethephon™, Fusilade Forte™, Moddus™, Moddus™ + Fusilade Forte™ combination, Ethephon™ + Fusilade Forte™ combination, and control (un-sprayed). 3Location: Wonji-Shoa and Metahara.

Figure 5: The effects of ripeners Ethephon™ (E), Fusilade Forte™ (FF), Moddus™ (M), Moddus™ + Fusilade Forte™ combination (M + FF), and Ethephon™ + Fusilade Forte™ combination (E + FF) on cane and sucrose yield. Mean values followed by the same letter in this study [35].

3.2.3. Sucrose Yield. The ripener main effect was significant ($p = 0.001$) on sucrose yield (t/ha)$^{-1}$; however, none of the interactions with ripeners were significant (Table 2). The ripener treatments Moddus™ + Fusilade Forte™ combination and Ethephon™ + Fusilade Forte™ combination resulted in the highest sucrose yields of 12.26 and 12.18 t/ha$^{-1}$, respectively, and were the only treatments that differed significantly from the control (unsprayed) treatment (Figure 5).

The significantly higher sucrose yield obtained from the combination Moddus™ + Fusilade Forte™ and Ethephon™ + Fusilade Forte™ combination treatments could be attributed to the significant increase in sucrose content that exceeded the other treatments (Figure 5) and the absence of any negative effect of these treatments on cane yield (Figure 4). In line with the current results, other studies [33, 35] also confirmed the sucrose yield improvement from the 2-chloroethyl-phosphonic acid and fluazifop-p-butyl combination treatment. van Heerden [41] also demonstrated that compared with the sole Ethephon™ and Fusilade Forte™ treatments, the Ethephon™ + Fusilade Forte™ and the Moddus™ + Fusilade Forte™ combination treatments performed better in terms of sucrose yield increase.

3.3. Economic Analysis. A maximum net benefit of USD 6765.08 ha$^{-1}$ was obtained from the combination treatment of Moddus™ + Fusilade Forte™ followed by the combination treatment of Ethephon™ + Fusilade Forte™ (USD 6733.83 ha$^{-1}$). The lowest field benefit of USD 6016.27 ha$^{-1}$ was obtained from the control treatment (Table 3).
The highest marginal rate of return of 4094% was obtained from the Fusilade Forte™ sole treatment followed by the Ethephon™ + Fusilade Forte™ combination (1479%), Moddus™ (1196%), and Ethephon™ (768%). The highest marginal rate of return in the sole Fusilade Forte™ treatment was due to the deflated cost of ripening (the chemical and its spraying costs) (Table 3). Since net field benefit and marginal rate of return are not a final criterion for recommendation of the best ripener treatment as they do not account for returns on investment (residuals), returns on investment were also calculated (Table 3). The maximum returns on investment was obtained from the Moddus™ + Fusilade Forte™ combination treatment (USD 6704.90 ha⁻¹⁻¹).

Therefore, the most economical option was derived from the Moddus™ + Fusilade Forte™ combination treatment with a marginal rate of return of 1244% (Table 3). In general, the marginal rate of returns obtained in all the ripener treatments compared with the control (unsprayed) treatment were greater than 1 (Table 3), which is above the minimum value (50%) assumed.

### Data Availability

The data used to support the study were obtained from Ethiopian Sugar Research Main Center.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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