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Determination of Critical Weed Competition Period in Roselle Plant (Hibiscus Sabdariffa L.) in Arba Minch, Southern Ethiopia

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Abstract

High weed infestations are among the greatest constraints to roselle production in the major growing countries worldwide. Realizing the critical period on behalf of weed control can be a means for an effective weed control strategy, which helps to reduce the raid of weeds and increase the benefits obtained from roselle production. The field experiment was conducted during the 2017 cropping year to determine (i) The critical periods of crop-weed competitions in roselle production and (ii) The effects of weed competition periods on growth and yield performances of roselle. The experiment consisted of 14 treatments in two series, including Increasing Duration of Weedy Periods (IDWP) and Increasing Duration of Weed-Free Periods (IDWFP), which were compared with a Weedy Check (WC) and Weed-Free Check (WFC). The treatments were arranged in randomized complete block design with three replications. Weeds were permitted to vie with the roselle for 15, 30, 45, 60, 75, and 90 Days After Transplanting (DAT) and throughout the growing periods along with a WFC. The results obtained from this study exhibited that a total of 69 weed species competed with roselle, the weeds abundantly belonged to Poaceae and Asteraceae families. In IDWP, weed density and dry biomass were increased, whereas crop parameters were decreased. The reverse was true in IDWFP both for weed and crop parameters considered. The highest fresh and dried calyx yields were obtained from WFC, and followed by 90 DAT in IDWFP, while the lowest was gathered from WC and followed by 75 DAT and 90 DAT in IDWP. The high weed interference significantly reduced fresh and dried calyx yield by 68.69% and 65.93% as compared to the yield received from the WFC, respectively. To determine the beginning and the end of the critical period of crop-weed competitions 5% and 10% arbitrary yield loss levels were used, which were determined by fitting Gompertz and logistic regression analysis. Overall, to reduce the yield loss by more than 5% and get a higher economic return, weeds must be kept free within 20 DAT to 75 DAT as it has been proved to be the critical period of weed-crop competitions. However, further studies have to be undertaken elsewhere in Ethiopia for at least three consecutive years for developing a concrete recommendation.

Keywords: Critical period; Dried calyxes; Fresh calyxes; IDWFP; IDWP; Roselle; Yield losses

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Introduction

CRoselle (Hibiscus sabdariffa L.) is a shrub crop and belongs to the family of Malvaceae, locally it is called “karkade”. It is one of the important medicinal crops and grown in different countries of the world. The crop is specifically well known in the tropical countries where it was native to Southeast Asia and tropical Africa [1,2]. The crop is known as roselle, razelle, sorrel, red sorrel, Jamaica sorrel, Indian sorrel, Guinea sorrel, sour-sour, and Queen’s land jelly crop in the different countries of the world [3]. It is grown mainly as medicinal plants in traditional farming systems. Also, it is known as an important cash crop and source of income for small-scale farmers in the cultivating areas. The economic part of the crop is mainly the fleshy calyx (sepals) and the surrounding fruit (capsules). In addition, in many parts of the world leaves is consumed as a green vegetable, the stem serves as a source of pulp for the paper industry, seeds used as a poultry feed and as an aphrodisiac, coffee substitute, and raw material used for industrial and domestic purposes [4,5].

Worldwide, roselle is acknowledged for its enormous unexploited economic advantages that have been seen by producers and end-users [4,5]. Although production of roselle is high under Ethiopian conditions, it is in the infant stage and grown primarily for commercial purposes only on a limited number of private farms [6,7]. Thus, with little or no recognition of its importance by the farmers and private owners for the cost of production concerning weed infestations, roselle has got little reflection to embark on its production. Moreover, the contribution of this crop is not as important as other cultivated crops to the country's growth and development, though in recent times few cooperatives are assisting in the production and supplying it as essential oils and medicinal herbs in small quantities to a national and foreign market. The reasons were the diverse agro-ecology that suited for growing various medicinal crops with a vast impending for roselle production in both rainfall distributions and irrigation conditions. Also, the country has a huge potential in internal and external markets possibly produced by the farming communities. Yet, these potentials and economic importance of the crop, the overall yield, and quality are lowered in both farmer and private farms mainly due to biotic and abiotic factors. Biotic factors included increased pressure of insect pests, diseases, and weeds. Abiotic factors mainly include poor cultural practices and harvesting constraints during the growing periods. Amongst biotic factors, weeds cause significant effects on the yield of roselle and play the greatest role in the production systems.

Weeds are plants growing where they are not wanted that compete with cultivated crops for nutrients, water, light and space. They exert a lot of harmful effects on the crop if they are not appropriately handled at a critical period [8]. Competition implies that the tendency of neighboring crops to utilize the same quantum of light, ions of mineral nutrient, molecules of water or volume of space. As a consequence, they may considerably trim down crop yields, dry matter and harm crop quality, which results in financial loss to the grower. According to Ayeni's report, the number one pest which farmers contend with within the crops was weeds. Parker et al. and Froud-Williams [9] also reported that weeds are considered as responsible for 5% in commercial, 10% in semi-commercial, and 20% in subsistence agriculture in reduction of crop yields, including roselle. Ahmed et al. [5] and Upadhyay et al. reported that roselle yield losses due to weed infestation were ranged from 45% to 90.17% in Sudan. Zimdahl reported that delayed weeding until late stages could result in irreversible damage to the crop. In the study areas and the country as well, the growers spend about 70% to 80% of their total available farm labor on weed control in the course of crop production, including roselle, without considering the critical time.

To determine appropriate time of weed management and efficient uses of herbicide for a given crop, identification of critical period is essential during the growing period; it helps determine the crop growth stages most assailable to weed competition [10,11]. The critical period defined by Hall et al. [12] and Knezevic et al. [13] is a number of weeks after crop emergence, during which a crop must be weed-free to prevent yield losses greater than 5%. Thus, the time of weed control measure is an important tool for maintaining optimum crop yields. Also, the Critical Period for Weed Control (CPWC) is a fundamental constituent of any management strategies in weed control options. Determining the critical periods of weed completion could help decrease yield losses due to weed interference. Therefore, understanding the critical period of weed competition in an open environment is one of the most crucial gears for developing a suitable and economically safe weed management strategy. Thus, this is environmentally friendly with no residual effects on the crop by identifying the most favorable time for the optimum Integrated Weed Management (IWM) program.

Cruser et al. suggested that the development of an appropriate IWM system demands the precise study of weeds and their interference with the crop grown. Despite being an important biotic factor, weed, in roselle production, there has been no detailed empirical research on the actual effects on yield and associated yield loss in the study areas and the country as well. In addition, victims resulting from their antagonism did not document in the study areas and the country as well. Identification and determining effective critical weed competition periods are the initial steps in tailoring responses for the management of the weeds. Therefore, the objectives of the study were to determine (i) The critical period of crop-weed competition in roselle production, and (ii) The effect of weed competition periods on the growth and yield performance of roselle at Arba Minch in southern Ethiopia.

Material and Methods

Description of the experimental site

The study was carried out in Arba Minch agricultural research center at Chano mile sub-station during the 2017 main cropping season with irrigation supplementary. It is geographically located at 06° 06' 841'' N latitude and 037° 35' 122'' E longitude. The site is located at an altitude of 1216 m above sea level in the plateau of the southern part of Ethiopia about 476 km south of Addis Ababa and 280 km from Hawasa, the capital city of Southern nations nationality and peoples' region in the environs of Abaya and Chamo lakes, Ethiopia. The areas are characterized by a bimodal rainfall pattern where a short rainy season (March and April), and the main rainy season (August and November). The area receives an average annual rainfall and temperature for the last decade was 750 mm and 27.5°C, respectively. The detailed descriptions of weather conditions of the 2017 cropping seasons are presented in Table 1. The soil is characterized by moderately alkaline with low organic contents (1.05%) and black sandy-loam in the soil type (Table1).

Seedling raising and transplanting

Following the standard method developed for roselle, raise of seedling was made on well-prepared seedbeds. Roselle seed, Sudan type, was obtained from Wondo Genet agricultural research center, Ethiopia institute of agricultural research. Seedlings were raised on the beds with a width of 1 m and 10 m length on raised seedbed type at the nursery. The polyethylene tubes, which filled with the recommended proportion of forest soil, sand, and topsoil [1:2:1], were used to develop the seedlings. The seeds were sown at a depth of 0.5 cm on 04 August 2017 cropping season. Grass mulch was applied on well-arranged polyethylene tubes after the seed was sown on the bed and removed after seven days when the seedlings have emerged. The polyethylene tubes were weeded and irrigated as deemed necessary. The plots of the main investigational field were meticulously armed and leveled, and subsequently, the ridges were armed and on sides of which transplanting was done. Healthy looking, vigorous, and uniformly sized seedlings were transplanting to the main field. Seedlings were transplanted at an appropriate stage at 30 days after sowing, 05 September 2017.

Table 1: Monthly mean minimum and maximum temperature, rainfall and relative humidity in Arba Minch areas, Southern Ethiopia, during 2017 main cropping season. NA: Data not available from the meteorological stations at the research center during the study periods. The data were obtained from national meteorological agency, Hawassa branch(2017)

Weather	**Monthly mean temperature, rainfall, and relative humidity (RH) in 2017 main cropping season**											
variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum (oC)	32.85	35.05	34	32.11	29.45	NA	25.9	23.22	25.73	27.6	27.78	29.75
Minimum (oC)	15.96	16.09	19.1	18.24	18.88	NA	18.31	18.67	17.48	18.16	16.02	16.65
Rainfall (mm)	1.5	2.7	57.1	122.4	177.5	NA	40.57	72.48	91.37	161.01	110.92	3.72
RH (%)	40.76	36.29	42.73	59.07	69.07	NA	56.04	57.32	69.02	64.54	63.72	NA

Experimental treatments, design, and trial management

The experiment was laid out in a randomized complete block design with three replications. The study has consisted of 14 treatments. These 14 treatments were applied in two sequences such as weedy interference up to 15, 30, 45, 60, 75, and 90 Days After Transplanting (DAT) (Increasing Duration of Weedy Period (IDWP)), and weed-free up to 15, 30, 45, 60, 75 and 90 DAT (Increasing Duration of Weed-Free Period (IDWFP)) competition periods were compared with two checks. The two checks include complete Weed-Free Check (WFC), no weed at all, and Weedy Check (WC), weedy in the rest of the growing period. Each treatment was assigned randomly to the experimental units within a block using a method described by Gomez et al. Similarly, the treatments were arranged following the method described by Nieto et al. Treatments of IDWFP were kept weed-free until 15, 30, 45, 60, 75 or 90 DAT, and afterward, they were left to weed infestations until harvesting dates (134 days). In IDWP, weeds were allowed to vie with roselle from transplanting until 15, 30, 45, 60, 75 or 90 DAT, and then the plots were weeded and reserved for weed-free awaiting harvesting dates. Control plots were set aside free of weeds (WFC) and allowed for weedy (WC) through the growing periods (114 days).

The layout was 71.40 m × 16.80 m with a unit plot size of 3.60 m × 3.60 m length and width, respectively. The layout was laid on five years fallow period land after clearing the existing plant population. The plots and blocks were spaced at 1.5 m and 2.5 m, respectively. Similarly, each plot consisted of a total of six rows and four harvestable middle rows. Spacing between plants and rows was maintained as 60 cm and 60 cm, respectively. In each row, there were six plants with a total of 24 plants per plot, excluding the border rows. The recommended agronomic practices for the growing of Roselle were applied uniformly during the field management, except for treatment application. Due to the available soil moisture and favorable environmental conditions, the weeds were emerged after five DAT and got fully developed after one week. Weeding was performed with the days given to each treatment and continued according to the days scheduled for each treatment, too. The frequency of weeding on the weed-free plots was applied to the appearance of weeds. Weeds were removed by hand pulling and hoeing.

Weed parameters assessment

Mixed weed species populations were used to determine the critical period of weed completion for general weed interference. Weed species found at each plot were recorded prior to weeding practice. Weed species recording and identification were made from three places diagonally within the plots using 0.5 m x 0.5 m quadrats (0.25 m2). Weed species identification was made using a weed identification book illustrated and organized by Stoud et al. [14] and botanical herbarium was collected and preserved by the Arba Minch crop protection clinic. The weed species found within the sample quadrats were identified and assorted into their respective groups. The collected weed data were summarized following the procedures as suggested by Akobundu et al. [15], Akobundu [16], Derksen et al. [17] and Magurran [18].

Weed frequency (it is the ratio of the number of occurrence of a given weed species to a total number of individuals of weed species multiplied by 100, (F(%)= x/N)), abundance (it is the population density of weed species expressed as the number of individuals of weeds per unit area, (A= ∑ W/N)), dominancy (abundance of an individual weed species concerning total weed abundance, (D=A*100/ ∑ A)), density and their respective relative values were determined as stated below. Likewise, Shannon's diversity index ($H'=\sum_{i=0}^{s} P_i \ln S$), where S was determined as the total number of species and Pi was the proportion of individuals of species i relative to the total number of individuals of all species), evenness (J' = H'i/H'max, i is individuals of each species and H' is diversity index value) and importance values (IV) of the species were also figured following Shannon [19] procedures. Importance value indicated that how dominant a species is in a given community. The IV of each species was calculated as the sum of the Relative Frequency (RF), Relative Abundance (RA) and Relative Dominance (RD) of species in the stand. Moreover, the Weed Density (WD) was determined as needed for knowing the potential impact on the economic yield of roselle in 90 DAT.

$$RF(\%) = \frac{Absolute\ frequency\ value\ for\ a\ species}{Total\ absolute\ frequency\ for\ all\ species} \times 100$$

RA (%) = (Absolute density for a given species)/(Total Absolute density for all species) x 100

$$RD(\%) = \frac{Absolute\ dominancy\ for\ a\ given\ species}{Total\ Absolute\ dominancy\ for\ all\ Species} \times 100$$

$$IV(\%) = RF(\%) + RA(\%) + RD(\%)$$

$$WD(per\ square\ meter) = \frac{Total\ number\ of\ weed\ species\ found\ in\ the\ plot}{Unit\ area\ of\ the\ plot}$$

Weed samples were harvested at ground level for dry biomass measurement. On plots of IDWFP, weeds were harvested at the time of crop maturity, while on plots of IDWP weeds, harvesting was done at the initial weed control time for each treatment, after which the treatment was kept clean of weeds. For weed dry biomass, the mixed weed species dropped within the quadrats were drawn from the ground immediately after recording and placed into kenaf-made bags separately treatment-wise. The samples were sun-dried for five to six days and subsequently were put into an oven at 70°C until a constant reading was maintained to measure dry biomass. The dry weight was expressed in kg ha-1.

Crop parameters assessment

Data on crop growth, phenology, and yield parameters were determined from each considered. The number of days to 50% flowering was recorded as a number of days from the DAT of roselle to the first flower that appeared on 50% of the plants in each plot. Plant height (m) was taken with a measuring rope from five randomly taken and pre-tagged plans in each net plot area from the base to the apex of the main stem at physiological maturity. A number of branches were recorded as the average number of reproductive branches per plant of the five sampled plants in the middle rows during harvesting time. The fresh weight of calyx (kg) was recorded from the four middle rows for each treatment and converted to kg ha-1. The dry weight of calyx was obtained from randomly selected 10 fresh calyxes for each treatment and put into the oven at 106°C for 24 hours, and then converted to kg ha-1. Fresh leaf weight (g) was taken from five pre-tagged plants from each plot and measured using electrical balance before physiological maturity. Hundred seed weight (g) was recorded as the weight of dried seeds after randomly selecting individual harvested pods. Seed weight (kg) was recorded from the four middle rows for each treatment and converted to kg ha-1. It was measured after lamming the sun-dried harvested pod from each net plot, and it was adjusted at 10% seed moisture content.

Data analysis

Data on weed and crop parameters measured were subjected to analysis of variance to determine the treatment effects using the general linear model procedure of the SAS software version 9.0. Prior to analysis, data on weed density and number of branches per plant data were transformed to normalize and make variance relatively independent of the means. To separate differences among treatment means Fisher's protected Least Significant Difference (LSD) test at $p \leq 0.05$ was used. On the other hand, to analyze the critical periods of weed control, the relative roselle yields (Y) of each treatment were computed as indicated below. It was used as the response variable in the regression analysis.

$$Y = \frac{H.sabdariffa\ yield\ in\ treatment}{H.\text{sabdariffa yield in weed free check}} \times 100$$

Similarly, Growing Degree Days (GDD), which was the accumulated thermal units at every 15 days during the growing period and the independent variable used in the regression analysis, was computed using the formula suggested by Andrade [20] as follows.

GDD=Σ [Daily average temperature-Base temperature], when daily average temperature >12°C

Where the base temperature during the growing period was estimated to be 12 °C; according to the federal office of the meteorological agency of Ethiopia at Hawasa branch (2017).

The beginning and end of the critical period, which is the duration mandatory for controlling weeds, was anticipated by the response curve when both curves arrived at 90% or 95% of the relative yield gain and 5% or 10% of the yield loss of the complete weed-free period. The critical period was ascertained and found to be between 90 and 95% or 5% and 10% threshold points. Gompertz and Logistic regression equations were used for depicting the effect of IDWFP and IDWP, respectively. The regression equations were fitted using the nonlinear procedure suggested by Knezevic et al. [10]. The Gompertz regression equation was as followed.

$$Y = a\exp\left[-b\exp(-kt)\right]$$

Where Y is the relative yield, a is the yield asymptote, b and k are constants, and t is the time of weed-free period from transplanting days (x-axis expressed in GDD). The Logistic regression equation was the following formula.

$$Y = \left[\frac{1}{\exp\left[\left(c*(t-d)\right]+f\right.} + \frac{(f-1)}{f}\right] \times 100$$

Where Y is the relative yield, t is the time in day's weeds competed from transplanting days (x-axis expressed in GDD), d is the point of inflection, and c and f are constants. The expression of this equation was modified from original Hall et al. [12] so that the point of inflection is not previously fixed to the fit in such a manner that it becomes the function of parameters f and c. Estimation of the parameter of nonlinear equations were found employing the technique of least squares using PROC NLIN of SAS version 9.0.

The critical weed-free period and the critical time of weed removal were deliberated by replacing relative roselle yield, fresh and dried calyx, as % of control, into the Gompertz and logistic regression equations. Yield losses of the Roselle to the highest level due to weed competition were calculated as followed.

$$Yield\ losses(\%) = \left[1 - \frac{H.sabdariff\ in\ weddy\ check}{H.sabdariff\ \ yield\ in\ weed\ \ freecheck}\right] \times 100$$

Partial budget analysis

The partial budget analysis is a method of organizing data and information about the cost and benefit of various agricultural alternatives. Gross Benefit (GB), Total Variable Cost (TVC), and Net Income (NI) were considered in the partial budget analysis. Gross benefit was obtained as the products of the market price and roselle yield, fresh and dried calyx. The total variable cost denotes the sum of all costs of variable inputs, whereas the NI is the difference between the GB and the TVC. The price of roselle was assessed from the prevailing local market. All costs were converted to per hectare basis in US dollar ($) for the proposed analysis. During the experiment, only the input cost of weeding was for the two series considered. All other costs of agronomic practices were uniform for all treatments. The costs' weeding was taken based on the prevailing wage rates in the locality. The cost of labor for all field management practices was on average $2.82 per labor per day during the 2017 cropping seasons. Similarly, information obtained through personal conversation with some traders indicated that the unit prices of fresh and dried calyx were averagely 10.56 and 10.05 $ kg-1 in the cropping year. The actual yield was adjusted reduced by 10% to reflect the differences between the experimental yield and the yield of farmers who could look ahead to the same treatment. It was assumed that there was optimum crop population density, timely labor availability, and better field management during the growing periods.

Results

Weed parameters

Weed communities: The present study revealed that the weed community in the investigational plots was composed of 69 weed

Table 2: Weed community recorded and their taxonomical characteristics in roselle field in Arba Minch, Southern Ethiopia, during the 2017 cropping season.

Family name	Scientific name	Seed type	Life form	Category	Life cycle
Malvaceae	Abutilon persicum	Broadleaf	Shrub	Broadleaf	Annual
Poaceae	Eragrostis cilianensis	Monocot	Grass	Grass	Annual
Poaceae	Dinerba retroflexa	Monocot	Grass	Grass	Annual
Poaceae	Digitaria abyssinica	Monocot	Grass	Grass	Annual
Poaceae	Digitaria horizontalis	Monocot	Grass	Grass	Annual
Poaceae	Cynadon nlemfuensis	Monocot	Grass	Siege	Annual
Poaceae	Chloris pilosa	Monocot	Grass	Grass	Annual
Poaceae	Sorghum arundianaceum	Monocot	Grass	Grass	Annual
Lamiaceae	Leucas martinicensis	Dicot	Herb	Broadleaf	Annual
Malvaceae	Hibiscus trionum	Dicot	Shrub	Broadleaf	Annual
Nyctaginaceae	Boerhaavia erecta	Dicot	Herb	Broadleaf	Perennial
Polygonaceae	Oxygonum sinuatum	Dicot	Herb	Broadleaf	Annual
Solanaceae	Datura stramonium	Dicot	Herb	Broadleaf	Annual
Solanaceae	Solanum nigrum	Dicot	Herb	Broadleaf	Perennial
Malvaceae	Corchorus trilocularis	Dicot	Herb	Broadleaf	Annual
Zygophyllaceae	Tribulus terrestris	Dicot	Herb	Broadleaf	Annual
Asteraceae	Crassocephalum rubeno	Dicot	Herb	Broadleaf	Annual
Euphorbiaceae	Euphorbia heterophylla	Dicot	Herb	Broadleaf	Annual
Euphorbiaceae	Acalypha crenata	Dicot	Shrub	Broadleaf	Annual
Tiliaceae	Corchorus olitorius	Dicot	Shrub	Broadleaf	Annual
Cyperaceae	Cyperus esculentus	Monocot	Siege	Siege	Perennial
Cyperaceae	Cyperus rotundus	Monocot	Siege	Siege	Perennial
Asteraceae	Tagetes minuta	Dicot	Herb	Broadleaf	Perennial
Amaranthaceae	Gonphrena celosoides	Dicot	Herb	Broadleaf	Perennial
Asteraceae	Launaea cornuta	Dicot	Herb	Broadleaf	Perennial
Asteraceae	Guizotia scabra	Dicot	Herb	Broadleaf	Perennial
Asteraceae	Bidens pilosa	Dicot	Herb	Broadleaf	Perennial
Asteraceae	Flaveria trinervia	Dicot	Herb	Broadleaf	Annul
Asteraceae	Ageratum conyzoides	Dicot	Herb	Broadleaf	Annual

Commelinaceae	Commelina benghalensis	Monocot	Herb	Broadleaf	Perennial
Commelinaceae	Commelina latifolia	Monocot	Herb	Broadleaf	Perennial
Lamiaceae	Ocimum basilium	Dicot	Herb	Broadleaf	Annual
Poaceae	Phalaris paradox	Monocot	Grass	Grass	Annual
Polygonaceae	Rumex abyssinica	Dicot	Herb	Broadleaf	Perennial
Acanthaceae	Hygrophila schulli	Dicot	Herb	Grass	Annual
Amaranthaceae	Amaranthus graecizans	Broadleaf	Herb	Broadleaf	Annual
Amaranthaceae	Amaranthus hybridus	Broadleaf	Herb	Broadleaf	Annual
Amaranthaceae	Amaranthus spinosus	Broadleaf	Broadleaf	Broad leaf	Annual
Poaceae	Paspalum scrobiculatum	Monocot	Grass	Grass	Perennial
Portulacaceae	Portulaca oleracea	Dicot	Herb	Broadleaf	Annual
Asteraceae	Galinsoga parviflora	Dicot	Herb	Broadleaf	Annual
Poaceae	Echinochloa colonum	Monocot	Grass	Grass	Annual
Boraginaceae	Cynoglossum lanceolatum	Dicot	Shrub	Broadleaf	Biennial
Cleomaceae	Cleome monophylla	Dicot	Herb	Broadleaf	Annual
Brassicaceae	Gynandropsis gynandra	Dicot	Herb	Broadleaf	Annual
Lamiaceae	Ocimum sanctum	Dicot	Herb	Broadleaf	Perennial
Lamiaceae	Hyptis suaveolens	Dicot	Shrub	Broadleaf	Perennial
Asteraceae	Xanthium strumarium	Dicot	Herb	Broadleaf	Annual
Asteraceae	Xanthium spinosum	Dicot	Herb	Broadleaf	Annual
Asteraceae	Biden pachyloma	Dicot	Herb	Broadleaf	Annual
Amaranthaceae	Chenopodium opulifolium	Dicot	Herb	Broadleaf	Annual
Asteraceae	Sonchus asper	Dicot	Herb	Broadleaf	Biennial
Solanaceae	Solanum anguivi	Dicot	Herb	Broadleaf	Perennial
Convolvulaceae	Ipomea eriocarpa	Dicot	Herb	Broadleaf	Annual
Asteraceae	Parthenium hysterophorus	Dicot	Herb	Broadleaf	Annual
Nyctaginaceae	Boerharia diffusa	Dicot	Herb	Broadleaf	Perennial
Amaranthaceae	Alternanthera pungens	Dicot	Herb	Broadleaf	Perennial
Poaceae	Erograstis tremulla	Monocot	Grass	Grass	Perennial
Asteraceae	Vernonia galamensis	Dicot	Herb	Broadleaf	Annual
Poaceae	Setaria pumila	Monocot	Grass	Grass	Annual
Pedaliaceae	Sesamum alatum	Dicot	Herb	Broadleaf	Annual
Poaceae	Setaria barbata	Monocot	Herb	Grass	Annual
Poaceae	Cenchrus ciliaris	Monocot	Grass	Grass	Perennial
Euphorbiaceae	Euphorbia hirta	Dicot	Herb	Broadleaf	Annual
Poaceae	Brachiaria eruciformis	Monocot	Herb	Grass	Annual
Poaceae	Digitaria ternate	Monocot	Grass	Grass	Annual
Poaceae	Eleusine indica	Monocot	Grass	Grass	Annual
Aizoaceae	Zaleya pentandra	Dicot	Herb	Broadleaf	Perennial
Cropaginaceae	Cropago lanceolata	Dicot	Herb	Broadleaf	Perennial

species, of which 45 were annuals, 2 biennials and 22 perennials types and comprised with 46 herbs, 15 kinds of grass, 2 sieges, and 6 shrubs (Table 2). About 27 families of weed species were identified, including poaceae, cyperaceae, amaranthaceae, commelinaceae, lamiaceae, nyctaginaceae, asteraceae, commelinaceae, cyperaceae, euphorbiaceae, convolvulaceae, polygonaceae, solanaceae, zygophyllaceae, portulacaceae, boraginaceae, tiliaceae, malvaceae, cleomaceae, brassicaceae, rubiaceae, passifloraceae, portulacacaeae, pedaliaceae, acanthaceae, aizoaceae, and cropaginaceae. At the same time, about 52 genera of weed species were also known. The dominant weed species family was poaceae with 17 species, followed by asteraceae 14 species. Out of the identified weed species, about 30.43% were classified as monocots and the rest were dicots, 69.57%.

Weed species composition: The frequency, abundance, dominancy, diversity index, and evenness of various weed species noted from the experimental plots were presented in Table 3. During the growing periods, frequently occurred weed flora were xanthium strumarium, galinsoga parviflora, brachiaria eruciformis, digitaria, amaranthus hybridus, cyperus esculentus, hyptis suaveolens, amaranthus graecizans, ageratum conyzoides, euphorbia heterophylla, and digitaria abyssinica. These 11 species represented 40.85% of the total weed population in the experimental plots. That is, weed species having a frequency of >2% and above were identified, and thereafter, referred to as prevalent weed species. Xanthium strumarium and galinsoga parviflora were among the most predominant species, followed by brachiaria eruciformis, digitaria ternate, amaranthus hybridus and cyperus esculentus in the plots. The diversity index assessed for the entire plots ranged between 2.62 and 7.80, while the evenness was ranged between 0.3365 and 1.00 in xanthium strumarium and ipomea eriocarpa (Table 3).

Similarly, the topmost weed species were identified based on RF, RA, RD, and IV. Weed species found in the asteraceae family were richer than the rest of the topmost families in species number and got greater area coverage. In this regard, asteraceae with seven species, followed by poaceae with three and commelinaceae, amaranthaceous, euphorbiaceae and cyperaceae correspondingly got two species in each of them. lamiaceae and portulacaceae have one species in each. xanthium strumarium, galinsoga parviflora, bidens pilosa, brachiaria eruciformi, digitaria ternate, amaranthus hybridus, cyperus esculentus, hyptis suaveolens, amaranthus graecizans, ageratum conyzoides, euphorbia heterophylla, digitaria abyssinica, crassocephalum rubeno, commelina benghalensis, acalypha crenata, commelina latifolia, cyperus rotundus, portulaca oleracea, launaea cornuta, and parthenium hysterophorus were found among the weeds species frequently observed and widely distributed. These weed species were the topmost abundant, important and problematic weed species (Table 4).

Table 3: Weed species composition and their distribution in the experimental plots in Arba Minch, Southern Ethiopia, during the 2017 cropping season.

Weed species	Frequency (%)	Abundance	Dominancy	Diversity	Evenness
Abutilon persicum	0.05	0.36	0.05	7.57	0.9704
Eragrostis cilianensis	0.17	1.17	0.17	6.39	0.819
Dinerba retroflexa	0.15	1.07	0.15	6.49	0.8315
Digitaria abyssinica	2.6	18.33	2.6	3.64	0.4667
Digitaria horizontalis	0.12	0.88	0.13	6.71	0.8601
Cynadon nlemfuensis	0.64	4.55	0.65	5.04	0.646
Chloris pilosa	0.16	1.12	0.16	6.42	0.8233
Sorghum arundianaceum	0.97	6.86	0.97	4.62	0.5928
Leucas martinicensis	1.47	10.38	1.47	4.21	0.5397
Hibiscus trionum	0.29	2.07	0.29	5.83	0.7472
Boerhaavia erecta	0.28	1.95	0.28	5.86	0.7517
Oxygonum sinuatum	1.11	7.83	1.11	4.49	0.5756
Datura stramonium	0.58	4.07	0.58	5.14	0.6586
Solanum nigrum	1.63	11.5	1.63	4.11	0.5264
Corchorus trilocularis	1.57	11.07	1.57	4.14	0.5312
Tribulus terrestris	0.2	1.38	0.2	6.2	0.7948
Crassocephalum rubeno	2.55	17.98	2.55	3.66	0.4692
Euphorbia heterophylla	2.85	20.1	2.85	3.55	0.455
Acalypha crenata	2.14	15.1	2.14	3.83	0.4916
Corchorus olitorius	0.46	3.21	0.46	5.37	0.6882
Cyperus esculentus	3.45	24.33	3.45	3.36	0.4306
Cyperus rotundus	2	14.1	2	3.9	0.5003
Tagetes minuta	1.43	10.1	1.43	4.24	0.5432
Gonphrena celosoides	1.57	11.1	1.57	4.14	0.5312
Launaea cornuta	1.77	12.45	1.77	4.02	0.5159
Guizotia scabra	0.35	2.45	0.35	5.64	0.7232
Bidens pilosa	5.01	35.33	5.01	2.99	0.3829
Flaveria trinervia	0.7	4.95	0.7	4.95	0.6345
Ageratum conyzoides	2.88	20.33	2.89	3.54	0.4537
Commelina benghalensis	2.19	15.45	2.19	3.81	0.4887
Commelina latifolia	2.09	14.76	2.09	3.86	0.4947
Ocimum basilic	0.15	1.05	0.15	6.49	0.8315
Amaranthus graecizans	3.04	21.45	3.04	3.48	0.4467
Amaranthus hybridus	3.82	26.98	3.83	3.26	0.4175

Amaranthus spinosus	1.34	9.45	1.34	4.3	0.5515
Paspalum scrobiculatum	1.45	10.21	1.45	4.22	0.5414
Portulaca oleracea	1.84	12.98	1.84	3.99	0.511
Galinsoga parviflora	6.99	49.33	7	2.65	0.3403
Echinochloa colonum	0.33	2.33	0.33	5.7	0.7307
Cynoglossum lanceolatum	0.22	1.55	0.22	6.1	0.7826
Cleome monophylla	1.31	9.21	1.31	4.32	0.5544
Gynandropsis gynandra	0.92	6.48	0.92	4.68	0.5996
Ocimum sanctum	0.36	2.52	0.36	5.61	0.7196
Hyptis suaveolens	3.09	21.76	3.09	3.47	0.4442
Xanthium strumarium	7.23	50.98	7.23	2.62	0.3365
Xanthium spinosum	0.07	0.5	0.07	7.23	0.9274
Biden pachyloma	1.48	10.41	1.48	4.19	0.5371
Chenopodium opulifolium	0.44	3.07	0.44	5.51	0.7061
Sonchus asper	0.18	1.24	0.18	6.2	0.7948
Solanum anguivi	0.28	2	0.28	5.79	0.7429
Ipomea eriocarpa	0.04	0.29	0.04	7.8	1
Parthenium hysterophorus	1.74	12.24	1.74	4.06	0.5211
Boerharia diffusa	0.28	1.98	0.28	5.86	0.7517
Alternanthera pungens	0.25	1.79	0.25	5.98	0.7662
Erograstis tremulla	1.48	10.45	1.48	4.2	0.5388
Vernonia galamensis	0.17	1.21	0.17	6.36	0.8155
Setaria pumila	1.17	8.26	1.17	4.44	0.5689
Sesamum alatum	0.13	0.93	0.13	6.63	0.8498
Setaria barbata	1.2	8.45	1.2	4.41	0.5656
Cenchrus ciliaris	0.57	4.02	0.57	5.15	0.6608
Euphorbia hirta	1.31	9.24	1.31	4.32	0.5544
Brachiaria eruciformis	4.6	32.45	4.6	3.07	0.3938
Digitaria ternata	4.3	30.33	4.3	3.14	0.4024
Eleusine indica	0.49	3.48	0.49	5.31	0.6802
Phalaris paradox	0.26	1.81	0.26	5.94	0.7612
Rumex abyssinica	0.1	0.69	0.1	6.89	0.8834
Hygrophila schulli	0.19	1.33	0.19	6.25	0.8013
Zaleya pentandra	1.34	9.45	1.34	4.3	0.5515
Cropago lanceolata	1.73	12.21	1.73	4.05	0.5188

Table 4: Topmost twenty weed species in terms of their relative frequency, abundance, dominancy and importance value (IV) in Arba Minch, Southern Ethiopia, during the 2017 cropping season

Rank	Weed species	Family	Common name	RF (%)	RA (%)	RD (%)	IV (%)
1	Xanthium strumarium	Asteraceae	Cocklebur	10.92	7.28	10.92	29.12
2	Galinsoga parviflora	Asteraceae	Gallant soldier	10.56	7.04	10.57	28.17
3	Bidens pilosa	Blackjack	Black jack	7.57	5.04	7.57	20.18
4	Brachiaria eruciformis	Poaceae	Signal grass	6.95	4.63	6.95	18.53
5	Digitaria ternata	Poaceae	Crabgrass	6.5	4.33	6.5	17.33
6	Amaranthus hybridus	Amaranthaceae	Green amaranth	5.77	3.85	5.78	15.4
7	Cyperus esculentus	Cyperaceae	nutsedge	5.21	3.47	5.21	13.89

8	Hyptis suaveolens	Lamiaceae	Pignut	4.67	3.11	4.66	12.44
9	Amaranthus graecizans	Amaranthaceae	Mediterranean amaranth	4.59	3.06	4.6	12.25
10	Ageratum conyzoides	Asteraceae	Goat weed	4.35	2.9	4.36	11.61
11	Euphorbia heterophylla	Euphorbiaceae	Milkweed	4.31	2.87	4.31	11.49
12	Digitaria abyssinica	Poaceae	Blue couch grass	3.93	2.62	3.93	10.48
13	Crassocephalum rubeno	Asteraceae	Rag leaf	3.85	2.57	3.85	10.27
14	Commelina benghalensis	Commelinaceae	Wandering Jew	3.31	2.21	3.31	8.83
15	Acalypha crenata	Euphorbiaceae	Copperleaf	3.23	2.16	3.23	8.62
16	Commelina latifolia	Commelinaceae	Watermaker	3.16	2.11	3.16	8.43
17	Cyperus rotundus	Cyperaceae	Nut siege	3.02	2.01	3.02	8.05
18	Portulaca oleracea	Portulacaceae	Purslane	2.78	1.85	2.78	7.41
19	Launaea cornuta	Asteraceae	Wild lettuce	2.67	1.78	2.67	7.12
20	Parthenium hysterophorus	Asteraceae	Congress weed	2.63	1.75	2.62	7

Weed density and dry biomass: The CPWC significantly affected weed density and dry matter production. The results of weed density and dry biomass were presented in Table 5. Significant differences (p<0.01) were detected among the durations of weed competition periods on these parameters measured. The results showed that significant reductions in weed density were observed in IDWFP plots. The weed density was increased significantly with each increase in competition periods. However, there was no significant distinction among the IDWP at 45, 60, and 75 DAT for the reduction of weed density. Likewise, no statistically significant difference was observed on weed density among IDWFP at 30, 45, 60, and 75 DAT although they showed a lower amount than

Table 5: Effect of increasing duration of weedy and weed-free periods on weed density and dry weight of Roselle plots in Arba Minch, Southern Ethiopia, during the 2017 cropping season. Means followed by the same letters within each column are not significantly different. Numbers with parentheses stand for untransformed data of mean weed density values. DAT: Days After Transplanting; IDWP: Increasing Duration of Weedy Period; WC: Weedy Check; IDWFP: Increasing Duration of Weed-Free Period; WFC: Weed-Free Check; CV: Coefficient of Variation and LSD: Least Significant Difference at 0.05 probability level.

Treatment	Weed density (m-2)1	Weed dry biomass (kg ha-1)
IDWP at DAT		
15	7.14 (51.11)cd	850.50fg
30	7.27 (52.91)bcd	916.30f
45	7.41 (55.17)abcd	1529.50d
60	7.44 (55.48)abcd	1757.60c
75	7.63 (58.90)abc	1810.00c
90	7.92 (62.94)ab	2209.40b
WC	8.05 (64.97)a	2779.00a
IDWFP at DAT		
15	7.47 (55.92)abcd	1653.10cd
30	7.06 (49.90)cd	1309.70e
45	7.19 (51.78)cd	944.50f
60	7.11 (50.72)cd	880.50f
75	7.21 (52.06)cd	836.80fg
90	6.98 (48.79)d	672.30g
WFC	6.98 (48.79)d	189.50h
LSD (0.05)	0.65	0.65
CV (%)	5.34	9.48

IDWP at the same dates. The highest reduction of weed density was observed on WFC and 90 DAT in IDWFP than WC. The highest weed dry biomass was obtained from WC, followed by 90, 75, and 60 DAT under IDWP. On the contrary, the lowest weed dry weight was found on WFC, followed by the date of 90 DAT in IDWFP (Table 5).

Crop parameters

Phenological and growth parameters: Days to 50% flowering: Significant (p<0.0001) difference was observed among the durations of weed competition concerning days to 50% flowering. It was increased with the IDWFP and decreased with the increasing IDWP. The highest days to 50% flowering was observed in IDWFP, although statistically on par with the values obtained slight differences among the treatments compared. The weed-free check and 90 DAT in IDWFP exhibited longer days to 50% flowering than the other periods. Conversely, no significant difference was exhibited in days to 50% flowering when weeds were allowed to grow from 60 DAT to 90 DAT, including WFC in IDWFP (Table 6).

Table 6: Effect of increasing duration of weedy and weed-free periods on phenological and growth parameters of roselle in Arba Minch, Southern Ethiopia, during the 2017 cropping season. Means followed by the same letters within each column are not significantly different. 1 Number with parentheses stand for untransformed data of a mean number of branches per plant values. IDWFP: Increasing Duration of Weed-Free Period; IDWP: Increasing Duration of Weedy Period; WFC: Weed-Free Check; WC: Weedy Check; CV: Coefficient of Variation and LSD: Least Significant Difference at 0.05 probability level.

Treatment	Phenological and growth parameters		
	50% date of flowering	Plant height (m)	Number of branches per crop1
IDWP at DAT			
15	34.46d	80.42bc	3.62 (3.00)abcd
30	30.13ef	63.67cde	3.27 (2.42)bcdef
45	30.06ef	60.83cde	2.73 (3.00)cdef
60	28.06f	60.83cde	2.39 (2.17)def
75	29.60ef	51.83de	2.27 (1.58)def
90	27.40f	50.67de	1.89 (0.67)ef
WC	27.86f	43.75e	1.70 (0.25)f
IDWFP at DAT			
15	29.53f	53.83de	2.71 (2.42)cdef
30	28.73f	67.50cd	3.39 (2.83)bcde
45	32.60de	62.67cde	3.58 (2.92)bcd
60	35.06cd	91.17ab	4.03 (11.42)abc
75	37.60bc	91.58ab	4.19 (12.17)abc
90	40.46ab	94.67ab	4.49 (9.25)ab
WFC	42.60a	111.67a	5.21 (13.42)a
LSD (0.05)	3.05	23.32	1.58
CV (%)	5.64	19.84	29.14

Plant height (M): It was significantly (p < 0.001) affected by the different durations of crop-weed completion. Plant height at different weed-crop competition periods was presented in Table 6. Increasing the duration of weedy periods resulted in a decrease in plant height, and the opposite was true for IDWFP. The results pointed out the higher the plant height, the lower the weed-crop competition period for weed population. The highest plant height was recorded on WFC and 60, 75, and 90 DAT in IDWFP. Significantly minimum plant height was recorded in WC under the IDWP. Comparison of the plant height in IDWP, the highest was recorded on 15 DAT. However, on days 30 to 90 DAT, including WC, there was no significant difference among the series, although there were statistically differences in parity with each day under the same category. The decrease in plant height reaches the level of significance when the competition period was increased from 15 DAT to 30 DAT. However, further increases in the competition periods resulted in insignificant plant height enhancement in IDWP.

A Number of Branches per Plant (NBP): It was an important character of roselle since it was greatly influenced by nutrient supply, soil moisture, and environmental stress. The results revealed that significant differences (p<0.01) were observed on the NBP at different crop-weed competition periods. No significant differences were retrieved from IDWP between 45 DAT to 90 DAT. In the IDWP, the 15 DAT and 30 DAT showed the highest NBP compared with the WC in the same line, which was statistical on par with the NBP at 45, 60, and 75 DAT. Likewise, there were no significant differences among IDWFP between 60 DAT to 90 DAT, including WFC. However, holding the plots weed-free from 15 DAT to 60 DAT resulted in a higher NBP, which was statistically on par with the NBP from WFC. Overall, the NBP were increased as weed interference decreased and vice versa (Table 6).

Yield parameters and yield losses estimation: Harvesting of the calyx was undertaken after 134 DAT. The fresh and dry weight of calyx, seed weight, hundred seed weight, and fresh leaf weight were significantly (p<0.05) affected by crop-weed competition during the growing periods (Table 7). In the IDWP, the highest fresh and dry weight of calyx, seed weight, and hundred seed weight were obtained from 15 DAT to 45 DAT, which was statistical on par with the values obtained from WC and 75 DAT and 90

DAT. In the same line, the highest fresh leaf weight was obtained from 15 DAT, followed by 30 DAT compared with WC and 90 DAT in IDWP and also statistically on par among them. Weedy plots up to 45 DAT were statistically on par with the rest of the IDWP components for the parameters studied, except for fresh leaf weight. In the IDWFP, increasing days from 30 to 90 DAT when the weeds were prohibited for growing up, no significant difference was observed on fresh and dry yields of the calyx. But a fresh yield of calyx was significantly affected only by WFC, whereas the dry yield of calyx was influenced by WFC and 90 DAT in the IDWFP components.

Regarding the seed and fresh leaf weight, the effects on weight of them were increased from 45 DAT to 90 DAT, including WFC, which was statistically on par with each other under IDWFP. However, no significant difference was observed on hundred seed weight when the weeds were removed from 15 DAT to 90 DAT in the same lines. The highest hundred seed weight was obtained from WFC compared with the rest of the treatments in both the IDWFP and IDWF. On the other, the losses that were imposed due to each of the different weed competition periods were considered relative to the yields of WFC for each of the IDWFP and IDWF. The results in loss analysis exhibited that the fresh and dry weight yields of calyx were higher in the days of 75 DAT and 90 DAT in IDWF, including WC, as compared to the WFC (Table 7).

Table 7: Effect of increasing duration of weedy and weed-free periods on yield parameters and yield loss of roselle at Arba Minch in Southern Ethiopia during the 2017 cropping season. Means followed by the same letters within each column are not significantly different. DYC: Dry Yield of Calyx; FYC: Fresh Yield of Calyx; FLW: Fresh Leaf Weight; HSW: Hundred Seed Weight; SW: Seed Weight; IDWFP: Increasing Duration of Weed-Free Period; IDWP: Increasing Duration of Weedy Period; WFC: Weed-Free Check; WC: Weedy Check; CV: Coefficient of Variation and LSD: Least Significant Difference at 0.05 probability level.

Treatment	Yield parameters					Yield loss (%)	
	FYC (Kg/ha)	DYC (Kg/ha)	SW (Kg/ha)	HSW (g)	FLW (g)	FYC	DYC
IDWP at DAT							
15	222.62bcd	40.39bc	49.88abcd	3.46b	15.91abc	40.15	38.37
30	189.30bcde	34.85bcd	43.36bcd	3.27bc	14.34bcd	49.11	46.83
45	171.79bcde	33.89bcd	42.86bcd	3.35bc	14.08cd	53.82	48.29
60	162.16cde	29.33bcd	41.74bcd	2.72cd	13.86cd	56.41	55.25
75	121.07e	26.68cd	36.17cd	1.98e	12.58def	67.45	59.3
90	116.57e	26.57cd	32.83cd	2.34de	10.76ef	68.66	59.47
WC	116.46f	22.33d	24.90d	1.97e	10.39f	68.69	65.93
IDWFP at DAT							
15	157.98de	30.98bcd	39.90bcd	3.23bc	13.76cde	57.53	52.74
30	217.97bcd	34.89bcd	47.38bcd	3.42bc	14.41bcd	41.45	46.76
45	222.12bcd	34.78bcd	53.38abc	3.46b	15.58abcd	40.29	46.93
60	237.02bcd	38.72bcd	63.01ab	3.49b	16.38abc	36.28	40.92
75	242.10bc	43.09bc	63.20ab	3.64b	16.39abc	32.32	34.26
90	251.76b	45.06b	74.00a	3.79ab	17.31ab	34.92	31.25
WFC	371.99a	65.54a	74.94a	4.47a	18.19a	0	0
LSD (0.05)	74.99	16.19	26.17	0.72	3.08		
CV (%)	24.66	29.41	31.86	13.66	12.68		

Critical periods of weed control: It was determined using the relatively fresh and dried yield of roselle (% of WFC) and GDD as quantitative variables in the regression analysis. The roselle transplanting date was used as the reference point for the buildup of GDD for describing the likelihood of weeds emerging before the roselle. Relatively the high values of coefficients of determination (R2) showed the Gompertz, and Logistic regression equations generally depicted the data were well for determination of parameters used in their equations for a relative yield of the fresh and dried calyx of roselle (Table 8).

The CPWC was carried out based on Arbitrarily Selected Yield Losses (AYL) of 5% and 10% to estimate the begging and end of the critical periods, which were guessed to be good enough, bearing in mind the current economics of weed control. The beginning of CPWC based on 5% AYL took place on 233 GDD, which was equivalent to 20 DAT, whereas the begging of CPWC based on 10% AYL occurred at 521 GDD, which was corresponding to 38 DAT. On the other hand, the end of the CPWC at 5% AYL happened on 1118 GDD, which was equivalent to 75 DAT, while the end of CPWC supported by 10% AYL occurred at 949 GDD, which was

Table 8: Parameter estimates for the Gompertz and Logistic regression equations for a relative yield of fresh and dried weight of roselle. a is the yield asymptote, b and k are constants, and t is the time in growing degree days. d is the point of inflection, c and f are constants, and t is the time in growing degree days.

Yield	Gompertz regression equation1				Logistic regression equation2			
	a	b	k	R2	c	d	f	R2
Fresh calyx	35.02	0.0384	0.0085	0.8	0.026	0.0038	3.84	0.9
Dried calyx	32.46	0.0398	0.0078	0.84	0.023	0.0021	1.86	0.96

corresponding with 65 DAT (Figure 1). Weeds should be controlled until 1118 GDD (relating to 75 DAT) in the study areas so as to reduce the yield losses up to 5% if it is possible rather than 10% yield losses were acceptable for roselle production.

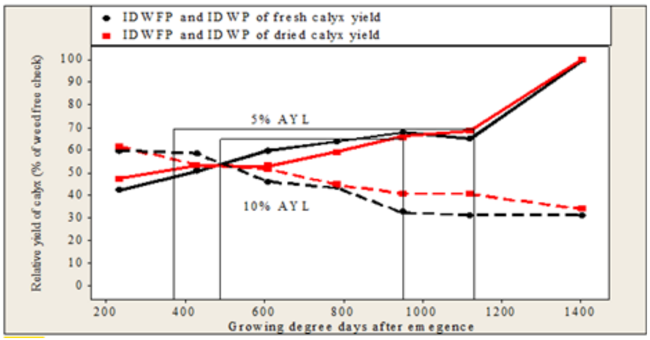

Figure 1 Effect of IDWFP or IDWP on roselle fresh calyx yield in Arba Minch, Southern Ethiopia, during the 2017 cropping season.

Partial budget analysis

A straightforward NI analysis was performed for each weed competition period to determine the profitability of weed control following the different CPWC. The results of the partial budget analysis and the data employed for its analysis were given in Table 9. The roselle is cultivated for its leaves, seeds and calyces yield (fresh and dried) worldwide. However, only fresh and dried yields of calyx were considered in the analysis since these two products are used dominantly worldwide and were mainly considered in the current study.

The highest NI of fresh yields of calyx was incurred from 15 DAT, followed by 30 DAT. The lowest fresh yield of calyx NI was recorded from 90 DAT in the IDWF series. In the IDWFP, the highest NI of fresh yields of calyx was computed from 90 DAT, followed by 75 and 60 DAT. While the lowest fresh yields of calyx were received from 15 DAT. The results obtained from 60 and 75 DAT in IDWFP were not significantly different between them for NI. On the other hand, the maximum NI of the dry yield of calyx was obtained from 15 DAT, while the lowest was recorded from 90 DAT in the IDWP. Likewise, the highest NI of the dry yield of calyx in IDWFP was computed from 90 DAT, followed by 45 DAT. Conversely, the lowest was incurred from 30 DAT and 46 DAT in the IDWFP. The partial budget analysis pointed out comparable to the whole treatments, the highest NI was obtained from IDWFP at WFC, while the lowest NI was recorded from WC in the IDWP. Overall, the NI of fresh and dry yields of calyx was increased with the IDWFP and decreased with the IDWP compared with WFC and WC, except the treatments at 15 DAT in the IDWP (Table 9).

Table 9: Results of economic assessment of increasing duration of weedy and weed-free periods on roselle plant in Arba Minch, Southern Ethiopia, during the 2017 main cropping season. GR: Gross Revenues; NI: Net Income; TVC: Total Variable Cost; IDWFP: Increasing Duration of Weed-Free Period; IDWP: Increasing Duration of Weedy Period; WC: Weedy Check; WFC: Weed-Free Check. The mean unit price of fresh and dried calyx per kilogram was \$10.56 and \$10.05 (at the exchange rate of 1\$ = 22.75 ETB) at the time of selling during the 2017 cropping season

Treatment	Fresh calyx yield					Dried calyx yield	
	Yield (kg ha-1)	Adjusted yield (kg ha-1) 10% down	TVC (\$ ha-1)	GR (\$ ha-1)	NI (\$ ha-1)	Yield (kg ha-1)	Adjusted yield (kg ha-1) 10% down
IDWP							
15	222.62	202.38	290.12	2137.13	1847.01	40.39	36.35
30	189.3	172.09	279.05	1817.27	1538.22	34.85	31.37
45	171.79	156.17	263.82	1649.16	1385.34	33.89	30.5
60	162.16	147.42	230.28	1556.76	1326.48	29.33	26.4
75	121.07	110.06	221.75	1162.23	940.48	26.68	24.01
90	116.57	105.97	195.42	1119.04	923.63	26.57	23.91
WC	116.46	105.87	152.93	1117.99	965.06	22.33	20.1
IDWFP							
15	157.98	143.62	188.68	1516.63	1327.95	30.98	27.88
30	217.79	197.99	303	2090.77	1787.77	34.78	31.3
45	222.12	201.93	311.44	2132.38	1820.94	34.89	31.4
60	237.02	215.47	335.17	2275.36	1940.19	38.72	34.85
75	242.1	220.09	382.03	2324.15	1942.12	43.09	38.78
90	251.76	228.87	390.93	2416.87	2025.94	45.06	40.55
WFC	371.99	338.17	431.73	3571.08	3139.35	65.54	58.99

Discussion

To combat the influence of weeds on agricultural production, proper management of weeds through either cultural or herbicidal or in a combination of different tactics, such as IWM, at the right time to reduce yield losses is a prerequisite. Several researchers reported that the critical period of weed competition is a fundamental component of an IWM program [8,20]. As reported by the farmers and private investors for the last three years (2015-2017), production of roselle was constrained by diversified noxious and socio-economically harmful weed species. These weeds have impacted the production of the roselle by creating difficulties during weeding practice, hard to control using herbicides and allelopathic effects. Thus, the importance, identifications and characterization of diversified weed species found in the roselle plant have not been studied. In addition to the major objectives, the present study was identified, characterized, and quantified major weed species found in roselle production. In the current study, about 14 treatments were comprised in two series to determine the CPWC for roselle in Arba Minch, Southern Ethiopia. As a result, better information was obtained regarding weed community, species composition, and CPWC for the roselle.

With the assessment made in the experimental plots, about 69 weed species were identified and constituted in 27 different families. The weed species were composed of the annual, biennial, and perennial types and categorized in broadleaf, grasses, and sieges (Table 2). Most of the weed species identified were in line with Mahadevan et al., Ahmed et al. [5] and Adjun [21] report that stated the weed species were composed of a wide range of annual, biennial, and perennial with comprised of broad-leaved, grasses and sieges weeds. Similarly, the results revealed that significant variations in weed species composition were observed under different weed completion periods. The high frequency, abundance, and dominancy of weed species indicate the high economic importance of these particular weed species. Likewise, variation in species diversity and evenness also were determined within the plots. The diversity and evenness values were dropped in the ranges of 2.62 to 7.80 and 0.3365 to 1.00, respectively. These assessed values of diversity and evenness for the entire plots were fallen within the range of those reported for weed communities in cropping systems [18,22].

The weed species diversity was relatively lower for the entire study period, which indicates the management option will follow similar tactics at the right time during the growing periods due to the higher similarity was exhibited on the plots. Likewise, the high abundance and dominancy of weed species could be attributed to the better rainfall distribution and constant irrigation supplementary during the shortage of rainfall, which is requisite by the crop that makes a favorable condition for the growth of the weeds, and as a result, the weeds made to thrive long period due to high infestation in the IDWP. The listed major weed species are amongst the major social, environmental, and economic threats to the farming communities in the study areas. Moreover, the results showed that there were positive and significant correlations among the weed parameters measured in species composition. That is, the higher the weed frequency, the higher would be its abundance and dominancy, and vice versa.

In increasing IDWP and decreasing IDWFP, there was an increase in the number of weed species under each treatment. The increasing frequency of weeding exhibited a lowered number of weed species infesting the plots. Under the IDWFP starting from 45 DAT to 90 DAT, the importance of individual weed species number was decreased. Whereas in the IDWP, the relative importance of these weed species was increased from 15 DAT to 90 DAT. The longer weeds were allowed to interfere might have resulted in the higher number of weed species contending with it and got the highest importance value. However, foremost individual weed species importance values were highest on WC than the WFC. The high importance values could be as a result of the incapability of the treatments to control these weed species or well-adapted of the weed species to the environment. Ahmed et al. [5], Akobundu et al. [15], Adjun [21], and Peer et al. [23] reported that such phenomenon could have resulted from the germination and regeneration capability of weed species within a short period as the effect of lengthened the weeding time interval.

The weed dry biomass weight accretion speculates the growth performance of weeds and gives a better signal of weed-crop competition. Greater weed dry biomass weight also reflects more exploitation of soil and the surrounding resources by weeds during the expenditure of crop growth. It was increased with the IDWP and decreased with the IDWFP. The likely reasons for the higher weed dry biomass weight could be due to relatively better rainfall and temperature along with supplementation of irrigation at the shortage of precipitation during the cropping periods, which might have brought on more buildup of weed dry biomass weight. Conversely, in IDWFP, the weeds came forth and grew after the respective weed-free periods under stress, and thus, resulted in less buildup of dry biomass weight. The lower weed density and dry biomass weight were found at 90 DAT and WFC under IDWFP, while the higher were recorded from 90 DAT and WC under the IDWP. This could be because an extended period of weeding practices did not encourage much weed growth. Several researchers in one or another way in different crops, including roselle, reported that these parameters had significantly influenced by the critical period of weed completion and different weed control methods, significantly decreased with the successive increase in the weed-free period [10,24,25].

In the current study, the results exhibited that IDWP and IDWFP were influenced the growth, phenology, and yield parameters. Plots left interfered with weedy for 30, 45, 60, 75, and 90 DAT, including WC, significantly lower the size of the growth, phenology and yield parameters. Whereas the plots allowed for weed-free for 30, 45, 60, 75, and 90 DAT, including WFC, showed relatively higher performance of growth, phenology, and yield parameters. In the IDWFP, this could be attributed to the avoidance of weeds from interfering with the roselle for prolonged periods, particularly at the critical period of crop growth, and minimum competition between the weeds and the roselle for the nearby resources necessary for their growth. This could result from the weeds might have less chance to compete with the crop due to the interference of weeding practices, and as result, the crop got a favorable condition to grow appropriately and undertake normal physiological function with no or little competition of resources with weeds during the growing period. In the IDWP, the resulted in lower performance of growth, phenology, and yield parameters were attributable to a prolonged period of weeds allowed to interfere with roselle. The probable reasons were higher weed infestation, lower weed control efficiency of the treatment considered, and severe competition with roselle for growth resources during the critical periods. Previous researchers reported that in many crops, including roselle, keeping the crop with weed-infested for long periods resulted in significant growth depression, and as a consequence, growth, phenology and yield attributes were reduced [24-27].

There is a period during the life cycle of a crop when it is most sensitive to the presence of weeds. This epoch is recognized as a critical period of competition [10,28]. Many researchers suggested that understanding and following CPWC is one of the most vital tools in IWM [10,26]. Similarly, the management of weeds supported with a critical period of weed competition is the most suitable approach to optimize weed control applications [29]. With the assist of this, it is achievable to make decisions on the need for and timing of weed control only when efficient weed control is required [11, 30]. Bearing in mind this justification in the determination of CPWC based on the AYL of 5% and 10%, which were determined by fitting Gompertz and logistic regression equations to the relative yield data, representing an increasing duration of weed-free and weed-interference periods, showed that the estimation was good enough allowing for the present economics of weed control. The results also demonstrated that the length of the weed-free period required to prevent yield loss varied with the accepted levels of yield losses.

The period in which weeds were possibly will compete with the crop devoid of more than 5% yield loss ranged from 233 GDD to 1118 GDD (20 DAT to 75 DAT). In comparison, when the yield loss levels of 10% were preferred, the period has fallen between 521 GDD to 949 GDD (38 DAT to 65 DAT). In this regard, the longer weed-free periods were less competitive of the crop or led to no further competition between crop and weed. Similarly, the higher the proportion of yield loss, the less time compulsory for the IDWP series was considered. Previous researchers reported in different crops exhibited the length of the critical period of weed control might vary depending on site-specific factors and the acceptable yield losses [10-12,25,31]. The beginning of critical weed competition became delayed and ended prior as the encoded AYL increased from 5% to 10%, and this variability is likely to be the competitiveness and regeneration nature of the weeds. This the current results were in agreement with the finding of Evans et al., Norsworthy et al. [27], Uremis et al. [30] and Amador-Ram´ırez worked on different irrigated and non-irrigated crops and reported that the end of CPWC was variable and highly dependent on density, competitiveness and emergence periodicity of the weed population.

However, the overall results of this study demonstrated that in all the CPWC, only the periods beyond 15 DAT in the IDWFP series significantly affected roselle's yield perhaps, because of the late start of the weeding practice after the weed appearance. Thus, suggested that reduced weed infestation starting early has the potential to control the weeds, particularly the first weeding practice made at an appropriate time of weeding as in the case of the 15 DAT to 90 DAT, including weed-free periods for a long time. But, only the 15 DAT in the IDWP has significantly increased roselle yields. In addition, roselle yields from the IDWFP series were invariably higher than the IDWP series. Partial budget analysis for CPWC was done to achieve economic use of weeding practices for critical periods of weed competition in the management of weeds in roselle to determine economically feasible CPWC. As a result, the highest NI of fresh and dry yields of the calyx was obtained from 90 DAT, followed by 75 DAT and 60 DAT in the IDWFP. However, prolonged crop-weed competition periods resulted in reduced fresh and dry yields of the calyx, which ultimately in higher yield losses for the roselle plant. Nevertheless, yield losses found out in this study could not be exclusively attributed to weed competition as some mechanical damages were recorded due to other pests, insect pests, and diseases, including the wild animals.

Conclusion

The outcomes of this study indicated that a total of 69 different weed species were identified, and the importance of each species was determined by scheming with the frequency, abundance, dominance, evenness and diversity, and importance values. The dominant families were poaceae with 17 weed species, followed by asteraceae with 14 weed species. The variation of weed density and dry matter weight showed the inverse to variation in crop growth, phenology, and yield parameters. This could be the result of minimum weed interference at critical weed completion periods of roselle and have a potential impact on weed growth and development due to IDWFP. The results of this study also showed that the highest fresh and dried calyx yields were obtained from WFC, followed by 90 DAT in the IDWFP. Whereas the lowest fresh and dried calyx yields were gathered from WC, followed by 75 DAT and 90 DAT in IDWP. About 68.69% and 65.93% yield losses due to the highest weed interference were registered from the WC in yields of the fresh and dried calyx, respectively. For both yields of calyx to prevent more than 5% yield loss, the efficient weed control methods could be carried out by keeping the crop weed-free between 273 GDD to 1118 GDD (20 DAT to 75 DAT). This could be done by using either cultural or chemical or IWM tactics. The results exhibited from partial budget analysis for both fresh and dried calyx yields, the highest NI was received from WFC, followed by 90 DAT and 75 DAT in the IDWFP, while the lowest was computed from WC, followed by 90 DAT in the IDWFP. Moreover, NI increased with the IDWFP and decreased with the IDWP, except for the treatments at 15 DAE in the IDWF. In general, the study was suggested to reduce the yield losses from more than 5% and get higher economic returns, weeds must be kept free inline within 20 DAT to 75 DAT to reduce the risk of economic yield losses as it is the critical period of weed-crop competition in roselle in the study areas. However, further studies have to be undertaken elsewhere in a similar environment where the crop is majorly grown for at least three consecutive years for developing concrete recommendations through the determination of a critical period of weed competition for efficient use of weed control tactics to augment sustainable roselle production.

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