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Agronomic and economic response of sorghum [*Sorghum Bicolor* (*L.*) Moench] to plant densities at Omonada in Jimma, southwestern Ethiopia

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Abstract
Field experiments were conducted at Omonada woreda for two consecutive years 2019 and 2020 main growing seasons at farmer's fields using Abamelko sorghum variety. The studies were conducted to identify a most or optimum favorable plant population, resulting uniform maturity and harvest to increase grain yield by discouraging its high tillering capacity. Fourteen treatments were arranged in randomized complete block design (RCBD) with three replications. Across season data analysis showed that most parameters of sorghum like stem diameter, dry above ground biomass, harvest index and grain yield were significantly affected by different densities except plant height. The highest dry above ground biomass and grain yield (11.65 t ha^{-1}) and (3.01 t ha^{-1}) respectively were recorded from the highest density (363636) and (181818) plants per hectare. In general grain and above ground biomass yield were showed a linear relation with plant population densities due to the morphological growth nature of the variety accommodating more plants per unit area. In conclusion, the partial budget analysis based on the field prices of production inputs and sorghum grain yield showed that the (166667) followed by (181818) ha^{-1} plant population density gave highest net benefit of (69105.19 EtB ha^{-1}) and (83327.77 EtB ha^{-1}) with acceptable MMR (301.69%) and (1027.90%) respectively Therefore, based on the current on-farm input availability and economic feasibility growth nature of sorghum Abamelko variety (166667) followed by (181818ha^{-1}) plant population density were recommended for farmer's profitability under rain fed condition in Omonada, Jimma zone.

Keywords: Grain yield, dry above ground biomass, plant population density

1. Introduction
An optimum plant population density is one of the most important factors in efficient resource utilization of crops and results high grain harvest. It was influenced by inter and intra row spacing of plant stand. Decreasing the distance between neighbor rows at any particular plant population has several potential advantages. First, it reduces competition among plants within rows for light, water and nutrients due to a more equidistant plant arrangement [1]. Secondly, the maximization of light interception from early canopy closure also reduces transmittance to bottom leaves canopies. The smaller amount of sunlight striking the ground decreases the potential for weed interference, especially for shade-intolerant species [2]. Thirdly the quicker shading of soil water being lost by evaporation [3]. Furthermore, earlier crop cover provided by narrower row width is instrumental to enhancing soil protection diminishing water runoff and soil erosion. The nutrient use efficiency can be improved with the use of an optimum plant population [4].
Sorghum can be drilled in a wide range of row spacing with different farmers and results in different plant population stands because it lacks proper tinning at an optimum density [5]. Reported that grain sorghum will likely be planted using the same equipment as planting soybean, corn or cotton and row spacing will be dependent upon the equipment the producer is currently utilizing. Research from other states has indicated that yields were maximized when using rows as narrow as 10 inches, especially when the crop was irrigated or when conditions were favorable for high yields. Though, optimal plant densities for grain sorghum differ from one region to another especially those that have different soil conditions [6]. Reported that crop row spacing's of less than 76 cm would increase grain yield in areas with high yield potential with little risk of reduced yield in areas with lower yield potential.

Row spacing and plant plant populations are variables that can have a significant impact on the net returns of sorghum producers. Sorghum cultivated in the Omonada area was 75*25 cm and has no definite spacing, especially between plants.

The more favorable planting pattern provided by closer rows enhances growth rate early in the season, leading to a better interception of sunlight, higher radiation use efficiency and a greater grain yield [7] and this Abamelko sorghum variety have the ability of high tillering capacity that leads to un-uniform in maturity and so that, was targeted to discourage tillering, increasing plant population and resulting uniform maturity to increase yield. But according to [8] plant population above critical density has a negative effect on yield per plant due to the effects of interplant competition for light, water, nutrient and other potential yields limiting environmental factors. So, that the research is initiated to optimal plant densities for grain sorghum to study area since it was differs from one region to another due to different factors.

2. Materials and Methods

2.1 Description of the Study Area

Field experiments were for two consecutive main growing seasons at Omonada woreda, Jimma Zone Southwestern Ethiopia at farmers' fields. The sites were located on 7º46' N and 36º 00'E and laid at an altitude of 1753 m.a.s.l. with soil type of the area is Upland: Chromic Nitosol and Combisol. The average maximum and minimum temperatures are 9 ºC and 28 ºC respectively and reliably receive good rains 1561 mm per annum cropping season (fig 1) below.

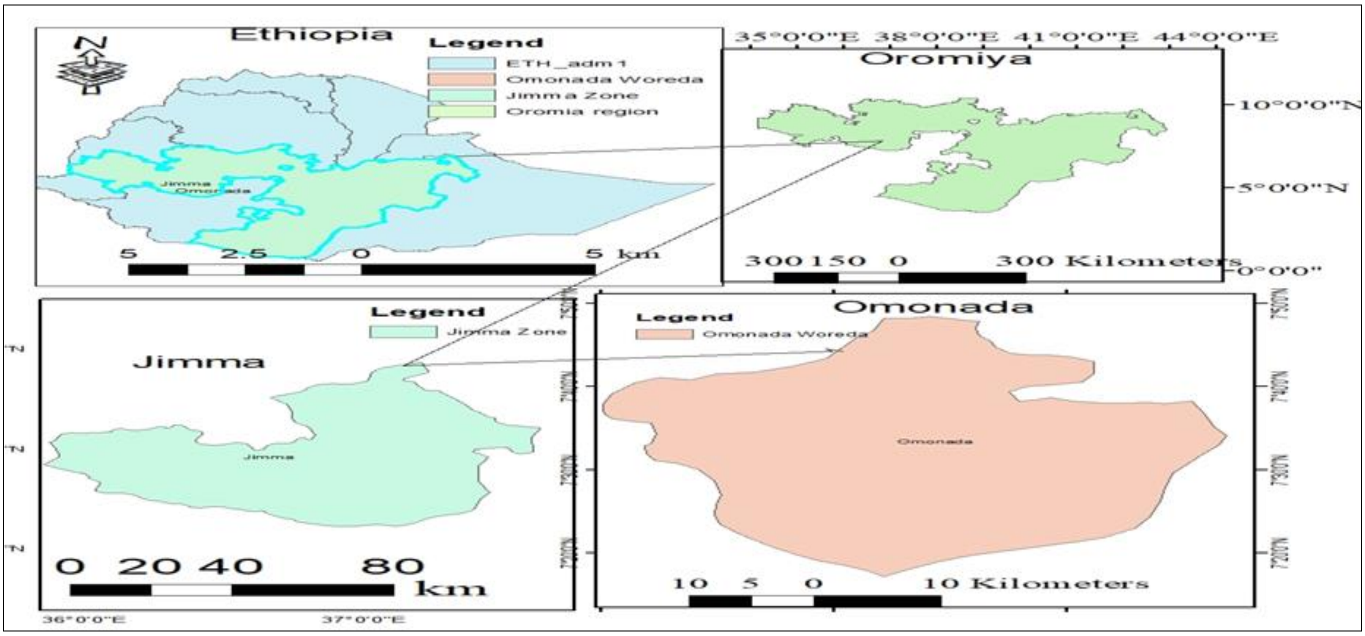

Fig 1: Location map of the study area, Omonada, Jimma Zone in Ethiopia

2.2 Description of the experimental materials

The plant material for the study was medium maturing sorghum varieties (Abamelko) used. It is the most promising variety released by Jimma Agricultural Research Centre (JARC) in 2001 and which adapted well to the agro-ecologies of the area and popularized.

2.3 Experimental treatment and procedures

The experimental field was ploughed and prepared with conventional tillage practice before planting at all experimental locations. The land was levelled using manual power before the field layout was made. The seeds were drilled in furrows and thinning was at seedlings good establishment to achieve target population. Fourteen plant population densities were selected including control (Table. 1) below. The treatments were arranged in randomized complete block design (RCBD) with three replications and plot size 22.5m^2 (4.5 m x 5 m) for each treatment was used. Each factor within a replication was randomly and each plot accommodates different numbers of rows based on intra row spacing. Nitrogen fertilizer was applied in a split in such a way that half during planting and half at the knee height growth stage to increase the nitrogen use efficiency. All other agronomic practices were applied uniformly to all experimental plots as per their respective recommendations for sorghum like three times hand weeding was done. The season rainfall pattern and other weather variables were suitable for sorghum growth and development except for shoot fly occurrence and controlled by chemicals.

Table 1: Treatments combinations of spacing and plant population.

S. No	Spacing (cm)	Plant population/Hectare	S. No	Spacing (cm)	Plant population/Hectare
1	55*5	363636	8	70*5	285714
2	55*10	181818	9	75*5	266667
3	60*5	333333	10	75*10	133333
4	60*10	166667	11	75*15	88889
5	60*15	111111	12	75*20	666667
6	65*5	307692	13	75*25	53333(control)
7	65*15	102564	14	75*30	44444

2.4 Data Collection and Measurement

All data were collected from ten plants based on guidelines for agronomy and soil fertility data collection in Ethiopia: National standard

2.4.1 Plant height: Plant height (cm)

Was recorded on ten random plants at maturity by measuring the height from the ground to the tip of the panicle.

2.4.2 Stem Diameter (girth)

Stem Diameter was measured and the average value of ten randomly taken plants stem 5cm above ground.

2.4.3 Dry Above ground Biomass yield

Dry above ground Biomass: Harvestable row plants were considered for the determination of above ground dry biomass weight by drying in sunlight till a constant dry weight was attained

2.4.4 Grain yield

Grain yield (q/ha) was recorded after harvesting from the harvestable rows. Seed yield was adjusted to 12.5% moisture using moisture tester (Dickey-john) and converted to quintal ha-1 for statistical analysis. Adjusted yield = Actual yield × 100-M/100-D; where M is the measured moisture content in grain and D is the designated moisture content (12.5%). where D is the designated moisture

2.4.5 Harvest index

It was calculated as the ratio of grain yield to total above ground dry biomass yield multiplied by 100 at harvest from the respective treatments [21]. Harvest Index = Grain yield/ above ground dry biomass yield × 100.

2.5 Partial budget analysis

To assess the costs and benefits associated with different sorghum plant population density done using the partial budget technique as described by [9]. An economic analysis was done using the prevailing open market prices for inputs at planting and outputs at the time the crop was harvested. All costs and benefits were calculated based on a hectare basis of Ethiopian Birr (EtB). The inputs and concepts used in the partial budget analysis were the mean grain yield of each treatment in both years, the field price of sorghum grain sale price grain minus the costs of labor for land preparation, planting, seed), the gross field benefit (GFB)/ ha^{-1} (the product of field price of the mean yield for each treatment), the field price of seed rate kg ha^{-1} and wage rate of application, the total costs that varied (TCV) which included the sum labor for land preparation, of field cost of seed and its wage for application. The net benefit (NB) was calculated as the difference between the GFB and the TCV. Actual yield was adjusted downward by 15% to reflect the difference between the experimental yield and the yield farmers could expect from the same treatment. There were optimum plant population density, timely labor availability and better management (e.g. weed control, rainfall) under the experimental conditions [9].

Dominance analysis procedure as detailed in [10] was used to select potentially profitable treatments from the range that was tested. The discarded and selected treatments using this technique were referred to as dominated and un-dominated treatments, respectively. The un-dominated treatments were ranked from the lowest to the highest cost. For each pair of ranked treatments, the percent marginal rate of return (MRR) was calculated. The MRR (%) between any pair of un-dominated treatments was the return per unit of investment in labor and seed. To obtain an estimate of these returns the MRR (%) was calculated as changes in NB divided by changes in cost. Thus, the MRR of 100% was used indicating for every one EtB expended there is a return of one EtB for a given variable input.

Sensitivity analysis for different interventions was also carried out to test the recommendation made for its ability to withstand price changes. It simply implied redoing the marginal analysis with the alternative prices. Through sensitivity analysis, the maximum acceptable field price of input was calculated with the minimum rate of return as described by [11].

2.6 Statistical analysis

The analysis of variance (ANOVA) for collected data was computed using R software version 3.5.3 statistical software R Core Team (2019-03- 11). Whenever the ANOVA results showed the significant differences between sources of variation, the means were separated using Fisher's least significant difference (LSD).

Table 2: Across season effect of plant population densities on plant height and girth of Sorghum at Omonada

Plant population Densities	Plant Height (cm)	Stem Diameter/ Girth (cm)
55*5(363636)	228.00	1.41b
55*10(181818)	225.17	1.35b
60*5(333333)	232.67	1.34b
60*10(166667)	235.33	1.55ab
60*15(111111)	232.50	1.47ab
65*5(307692)	228.17	1.44b
65*15(102564)	235.10	1.47ab
70*5(285714)	236.77	1.53ab
75*5(266667)	229.83	1.47ab
75*10(133333)	233.83	1.46ab
75*15(88889)	234.00	1.58ab
75*20(66667)	224.67	1.46ab
75*25(53333)	218.17	1.71a
75*30(44444)	225.33	1.56ab
Mean	29.97	1.49
LSD (0.05)	Ns	*
CV %	6.06	10.39

3. Results and Discussions

3.1 Plant Height

The result of plant height did not show a significant effect ($p < 0.05$) on the plant population density**.** The tallest plant height 236.77 cm was recorded from the highest (285714**)** plant population density and in contrast, the shortest (53333) plant height was recorded from one of the lowest densities. This implies that there was an increase in plant height with an increase in density a decline with further increase inconstantly (Table 2). The current result was in agreement with [12] report, moreover, as plant density increases to an optimal point, increases in plant height, total tiller number, leaf area index (LAI) and leaf area duration (LAD) are generally observed.

3.2 Stem diameter (Stem girth)

The result of stem diameter (Girth) was a highly significant effect ($p < 0.05$) on the plant population density. The highest stem diameter 1.71 cm was recorded from (53333) population density which was among the lowest density (Table 2). In contrast, the lowest 1.41 cm was recorded from the (363636) population density which was the highest density. The result showed that there was an increase in stem diameter with population density decreasing gradually. It's due to low competition to moisture, nutrients and sun radiation facilitates the growth of plants. Similarly, stem diameter decreased and plant height increased as plant density increased from 6.0 to 12.0 plant m-^{2} [13].

3.3 Above ground biomass yield

The results of the analysis of variance showed that above ground biomass of sorghum was significantly influenced by the main effect of plant population density (Table 3). The highest (11.65 t ha^{-1}) above ground biomass yield was recorded from (363636) but the smallest (1.26 t ha^{-1}) was recorded at the lowest (53333) plant population density (fig.2). It's obvious that an increase in seed rate results high in a plant height high due to computation to sun radiation, which results directly an increase in above ground biomass yield where no limitation of resources like moisture and nutrients. This might be due to plant population density having a linear relation with above ground biomass yield increase or due to a number of plants stands per unit area with good plant growth and development. The current result supported by [14] reported that high plant densities could be supported under conditions of high rainfall or irrigation, with increasing plant density resulting in a greater effective rooting depth, larger grain yield and improved water-use efficiency for biomass formation. Also as row spacing decreased and seed rate increased, tillering was hindered and the number of the main plant increased results in higher biomass. The result was in agreement with [15] reported that the higher plant populations, within row competition apparently reduced tiller production to approximately 0.1/plant.

Table 3: Across season effect of plant population densities on grain, dry above ground biomass yield and harvest index of Sorghum at Omonada

Plant population densities	Grain yield (ton ha^{-1})	Dry above ground biomass (ton ha^{-1})	Harvest Index (%)
55*5 (363636)	2.65ab	11.65a	28.52a-d
55*10 (181818)	3.01a	8.26a-c	38.76a-d
60*5 (333333)	2.59ab	8.97ab	34.21d-f
60*10 (166667)	2.53a-c	5.77b-d	43.23a-c
60*15 (111111)	1.93a-c	4.72d-d	38.04b-d
65*5 (307692)	2.53a-c	8.27a-c	36.59c-e
65*15 (102564)	1.66bc	4.77b-d	37.63b-d
70*5 (285714)	1.50bc	5.74b-d	29.27ef
75*5 (266667)	2.27a-c	7.99a-c	36.26a-c
75*10 (133333)	1.98a-c	4.36cd	42.55a-c
75*15 (88889)	1.83a-c	4.19cd	41.80a-c
75*20 (66667)	1.73bc	3.39d	44.90ab
75*25 (53333)	1.26c	3.09d	38.41a-d
75*30 (44444)	1.52bc	2.77d	45.81a
Mean	2.07	6.00	38.28
LSD (0.05)	*	*	**
CV %	23.57	22.10	11.27

3.4 Grain yield

The statistical analysis on grain yield was a significant response to plant population density ($p < 0.05$). The highest grain yield was 3.01 t/ha obtained from (181818) plant population density (fig 2). This may due to as row spacing decreased and seed rate increased, tillering was hindered and the number of the main plants increased results in high grain yield up to optimum spacing. Similarly [16] also reported that sorghum can take advantage of tiller production during optimal or above average conditions leading to near optimum yields. Generally, the current result is in agreement with the research that has suggested that decreasing tiller production can result in greater yield. [17] Reported that planting in clumps at higher densities decreased tiller production in sorghum which results in up to 100% increase in yields. But low density planted and produce tiller results un-uniform in maturity and leads to yield loss. Also, it was supported by [18] yield losses have been found to be greater under lowers than higher population. They found out that within row plant spacing causes higher yield losses. The grain yield increase with an increase in plant population density up to (363636) then starts to decline gradually to 2.65 t/ha. It' due to inter and intra specific computation to radiation and nutrients was beyond the optimum.

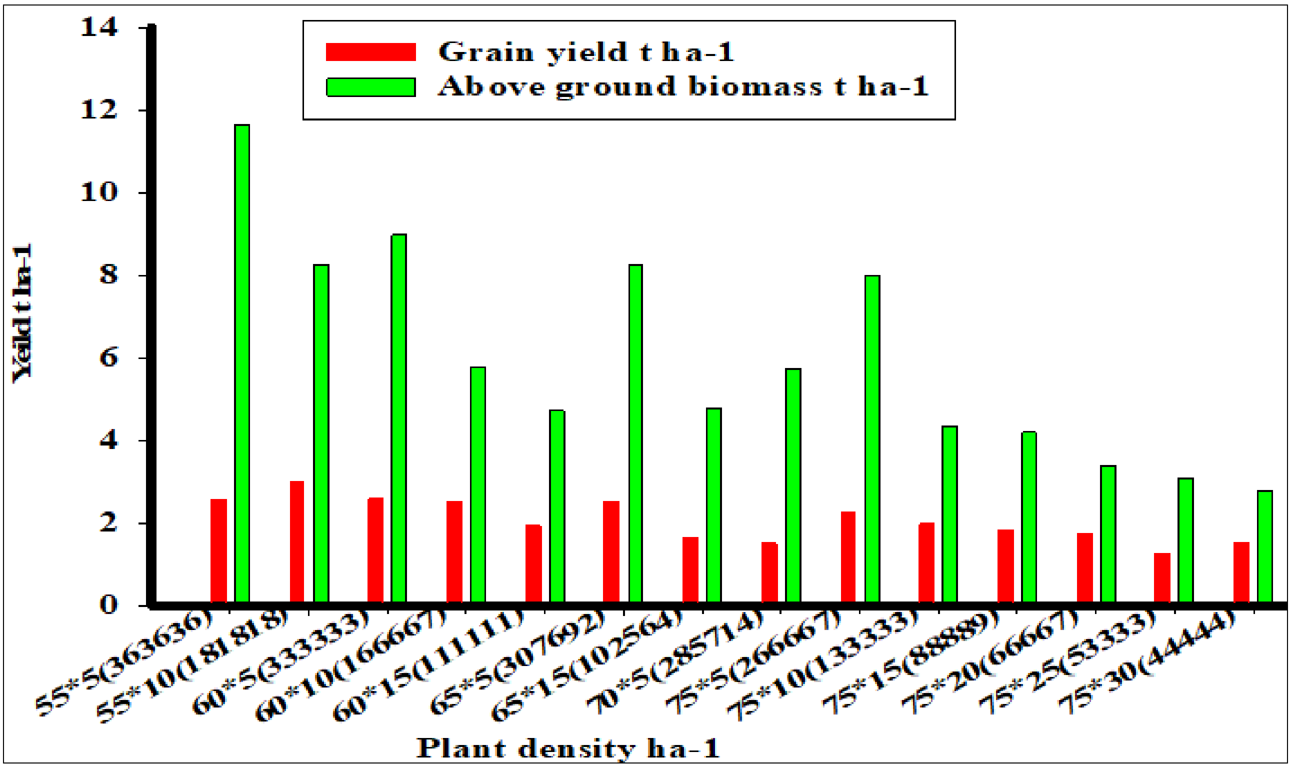

Fig 2: Graph of grain yield and dry above ground biomass

3.5 Harvest index

The effect of plant population density on harvest index showed a significant effect ($p < 0.01$) (Table 3). The highest 45.81% harvest index was recorded from (44444) and in contrast, the lowest 28.52 % was from (363636) plant population density (Table 3). The harvest index result showed that as density increases the decrease in harvest index. The result was in agreement with [19] the lowest plant density (11.11 plants^{-2}) established at a plant geometry of 60 x 15 cm resulted in the highest harvest index of 19.38 compared to other plant densities.

3.6 Economic viability of sorghum Abamelko plant population density

The analysis of variance (Table 3) showed that plant population density had a significant (P = 0.001) effect on the grain yield. An economic analysis of the results was done using the partial budget technique [9]. The data used in the development of the partial budget is given in (Table 3). It was performed by considering fertilizer, seed and labor costs for land preparation and application as main input, mean grain yield obtained across the season. The total costs of fertilizers (NPS = 15.90 EtB/kg and urea = 12.65 EtB/kg and sale of grain sorghum at around Omonada an open market average price (35.29 EtB/kg). Dominance analysis (Table 3) led to the selection of treatments (44444), (66667), (88889), (111111), (133333), (166667) and (181818) ha^{-1} plant population density were ranked in increasing order of total costs that vary. The treatment having MRR below 100% was considered and unacceptable to farmers; thus, (133333) ha^{-1} plant population density was eliminated [9] (Table 5). Therefore, this investigation remained with changes to (44444), (66667), (88889), (111111), (166667), (181818) ha^{-1} plant population density as promising new practices for farmers under the prevailing price structure since they gave more than 100% MRR. This might suggest the use of inputs that result in maximum net benefits [22]. Partial budget analysis based on the field prices of inputs and maize grain yield showed that, (166667) and (181818) ha^{-1} plant population density gave the Highest net benefit (69105.19 EtB ha^{-1}) and (83327.77 EtB ha^{-1}) respectively with acceptable MMR (676.36%) and (1390.69%) (Fig. 2).

The open market prices are ever changing and as such a recalculation of the partial budget using a set of likely future prices i.e., sensitivity analysis, was essential to identify treatments that remain stable and sustain satisfactory returns for farmers despite price fluctuations. The sensitivity analysis study indicates an increase in the field price of the total variable costs, and a fall in the price of sorghum grain, which represented a price variation of 15% (Table 5).

The price changes are sensitive under market conditions prevailing around Omonada. The new prices were thus used to obtain the sensitivity analysis (Table 5) Changing from treatments (44444), (66667), (88889), (111111), (166667) and (181818) ha^{-1} plant population density to (66667), (166667) and (181818) ha^{-1} plant population density with MMR (254.73%), (301.69%) and (1027.90%) respectively (Table 5) which were above the minimum acceptable MRR of 100% except for (44444), (88889) and (111111) ha^{-1} plant population density which was below the minimum acceptable MRR. These results agree with [20] whose findings from coastal Kenya on maize showed that the application of 30 kg N ha^{-1} consistently gave acceptable economic returns.

Therefore, due to the morphology of Abamelko, un like the other varieties it responds to the highest density (166667) and (181818) ha^{-1} plant population gives an economic yield response and also sustained acceptable under projected worsening trade conditions of study area or based on partial budget analysis (166667) and (181818) ha^{-1} plant population density with MMR (301.69%) and (1027.90%) respectively with a highest net benefit of (69105.19 EtB ha^{-1}) and (83327.77 EtB ha^{-1}) respectively was promising new practices to give an economic yield response and also sustained acceptable even under projected worsening trade conditions in Omonada, Jimma. Farmers could thus choose any of the two new ha^{-1} plant population densities depending on their resources.

Table 4: Partial budget analysis for plant population density at current prices.

Plant Population Densities	Grain Yield t ha-1	Adjusted Grain Yield t ha-1	Gross Field Benefit	TCV (EtB ha-1)	Net Benefit (EtB ha-1)	Dominance Analysis
75*30(44444)	1.52	1.37	48276.72	3000	45276.72	Un dominated
75*25(53333)	1.26	1.13	40018.86	3600.014	36418.85	Do dominated
75*20(66667)	1.73	1.56	54946.53	4500.068	50446.46	Un dominated
75*15(88889)	1.83	1.65	58122.63	6000.068	52122.56	Un dominated
65*15(102564)	1.66	1.49	52723.26	6923.139	45800.12	Dominated
60*15(111111)	1.93	1.74	61298.73	7500.068	53798.66	Un dominated
75*10(133333)	1.98	1.78	62886.78	9000.068	53886.71	Un dominated
60*10(166667)	2.53	2.28	80355.33	11250.14	69105.19	Un dominated
55*10(181818)	3.01	2.71	95600.61	12272.84	83327.77	Un dominated
75*5(266667)	2.27	2.04	72097.47	18000.2	54097.27	Dominated
70*5(285714)	1.5	1.35	47641.5	19285.89	28355.61	Dominated
65*5(307692)	2.53	2.28	80355.33	20769.42	59585.91	Dominated
60*5(333333)	2.59	2.33	82260.99	22500.2	59760.79	Dominated
55*5(363636)	2.65	2.39	84166.65	24545.68	59620.97	Dominated

TCV = total cost that varied, Retail price of grain = Birr 35.29 per kg; EtB = Ethiopian Birr; Fertilizers urea = Cost of Birr 12.65, per kg; NPs = Cost Birr 15.90 per kg; MMR= Marginal Rate of Return; NB = Net benefit;

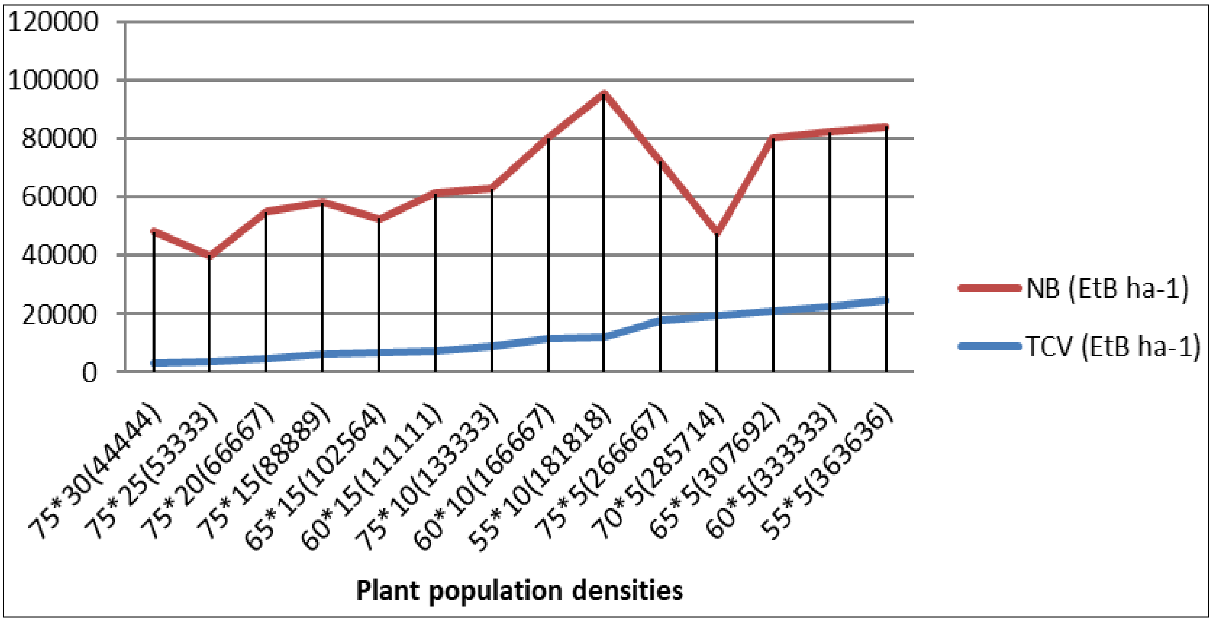

Fig 3: Graph of total cost that varied and net benefit of the plant population density

Table 5: Partial budget with estimated marginal rate of return (%) for plant population density at current prices.

Plant population densities	TCV (EtB/ha)	Net Benefit (EtB/ha	Raised Cost	Raised Benefit	MRR (%)
75*30(44444)	3000	45277	---	---	---
75*20(66667)	4500	50446.46	1500.07	5169.74	344.63
75*15(88889)	6000	52122.56	1500.00	1676.10	111.74
60*15(111111)	7500	53798.66	1500.00	1676.10	111.74
75*10(133333)	9000	53886.71	1500.00	88.05	5.87
60*10(166667)	11250	69105.19	2250.07	15218.48	676.36
55*10(181818)	12273	83327.77	1022.70	14222.58	1390.69

TCV= total cost that varied, Retail price of grain =Birr 35.29 per kg; EtB = Ethiopian Birr; Fertilizers urea = Cost of Birr 12.65, per kg; NPs =Cost Birr 15.90 per kg; MMR= Marginal Rate of Return; NB = Net benefit;

Table 6: Sensitivity analysis of sorghum production based on a 15% rise in total cost and sorghum price of gross field benefit fall

Plant population densities	TVC (ETB ha-1)	NB (ETB ha-1)	Increment Cost	Increment Benefit	MRR (%)
75*30(44444)	48276.72	3450	---	---	---
75*20(66667)	54946.53	5175.078	1725.08	4394.28	254.73
75*15(88889)	58122.63	6900.078	1725.00	1424.69	82.59
60*15(111111)	61298.73	8625.078	1725.00	1424.68	82.59
60*10(166667)	80355.33	12937.66	4312.58	13010.55	301.69
55*10(181818)	95600.61	14113.76	1176.11	12089.19	1027.90

TCV = total cost that varied, Retail price of grain = Birr 35.29 per kg; EtB = Ethiopian Birr; Fertilizers urea = Cost of Birr 12.65, per kg; NPs =Cost Birr 15.90 per kg; MMR= Marginal Rate of Return; NB = Net benefit;

4. Summary and Conclusion

Plant density plays a great role in increasing grain yield, especially for abamelko kinds of sorghum varieties due to their morphology. The grain yield was increased with an increase in plant density per unit area but with further increase, farmers didn't prefer due to the stem thinness and weakness that good for locally fence making. Among the important parameters stem diameter (girth), harvest index, above ground biomass and grain yield showed significant differences due to the plant population density but plant height was not. Partial budget analysis was done by including all treatments and the highest net benefit (69105.19 EtB ha-1) and (83327.77 EtB ha-1) obtained from (166667) and (181818) ha-1 plant population density with acceptable MMR (301.69%) and (1027.90%) respectively (fig. 2). Hence, to obtain the optimum economic return from the production of sorghum (Abamelko variety) at the study area, (166667) and (181818) ha-1 plant population densities had the highest comparable yield and economic net benefit. Therefore, (166667) and (181818) ha-1 plant population densities sustained and effective in attaining higher yield and economic benefit under projected worsening trade conditions in Omonada.

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Conflicts of Interest

There is no conflict of interest for this article.

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