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Corn crop responds positively to fertigation with black water from sewage treated by decentralized anaerobic system

Milho responde positivamente à fertirrigação com água negra oriunda de esgoto tratado por sistema anaeróbico descentralizado

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ABSTRACT

The basic sanitation systems are not enough to meet the sanitary requirements in the rural areas of Brazil. Hence, a decentralized anaerobic system was developed by Embrapa to enable the treatment of domestic sewage. The treated sewage effluent (TSE) should be applied to completely replace the N from mineral fertilizer required by corn plants, a typical crop cultivated by Brazilian smallholder farmings for animal feed. Hence, the purpose of this study was to investigate the corn crop responses to the use of TSE as fertilizer. A field experiment was carried out in a sandy clay loam soil at São Carlos, state of São Paulo, Brazil, over 2018-2019 summer growing season of a hybrid corn cultivar with dual aptitude (grain and silage production). Four treatments about application of different nutrient sources were evaluated in a randomized block design with three replications: 1- NPK: urea, simple superphosphate and potassium chloride as nutrient sources; 2- EfPK: TSE as N source + PK from mineral fertilizers; 3- Ef: TSE only; 4- PK: mineral fertilizers only. TSE was applied to crop by short and closed-end furrow irrigation. TSE can be used as a source of nitrogen mainly and other nutrients for corn crop nutrition based on the knowledge of effluent nutrient concentrations. TSE split application through fertirrigation can lead to corn yield parameters close to those from NPK application using only mineral fertilizers as nutrient sources. The reuse of this wastewater is feasible for small-scale corn production which is typical of Brazilian smallholder farming.

Index terms: Biodigester septic tank; nitrogen; furrow irrigation; small farmer.

RESUMO

Os sistemas de saneamento básico não são suficientes para atender as necessidades sanitárias nas áreas rurais do Brasil. Assim, um sistema anaeróbio descentralizado foi desenvolvido pela Embrapa para viabilizar o tratamento de esgoto doméstico. O efluente de esgoto tratado (EET) pode ser aplicado para substituir totalmente o N oriundo do fertilizante mineral requerido pelas plantas de milho, espécie vegetal típica cultivada por pequenos produtores brasileiros para alimentação animal. Assim, o objetivo deste estudo foi investigar as respostas da cultura do milho ao uso de EET como fertilizante. Um experimento de campo foi realizado em solo franco argilo arenoso em São Carlos, estado de São Paulo, Brasil, na safra de verão 2018-2019 utilizando uma cultivar de milho híbrido com dupla aptidão (produção de grãos e silagem). Foram avaliados quatro tratamentos sobre a aplicação de diferentes fontes de nutrientes, dispostos em blocos casualizados com três repetições: 1- NPK: uréia, superfosfato simples e cloreto de potássio como fontes de nutrientes; 2- EfPK: EET como fonte de N + PK de fertilizantes minerais; 3- Ef: apenas EET; 4- PK: apenas fertilizantes minerais. O EET foi aplicado na cultura por irrigação por sulcos curtos e fechados. O EET pode ser utilizado principalmente como fonte de nitrogênio e outros nutrientes para a nutrição da cultura do milho com base no conhecimento das concentrações de nutrientes do efluente. A aplicação fracionada de EET por fertirrigação pode levar a parâmetros de produtividade do milho próximos aos da aplicação de NPK utilizando apenas fertilizantes minerais como fonte de nutrientes. O reaproveitamento desse efluente é viável para a produção de milho em pequena escala, típica da agricultura familiar brasileira.

Termos para indexação: Fossa séptica biodigestora; nitrogênio; irrigação por sulco; pequeno produtor.

INTRODUCTION

In Brazil, 23% of rural households were served by a waste water collection network or septic tank for excreta or sewage in 2016 (United Nations Water Global Analysis and Assessment of Sanitation and Drinking-Water - GLASS, 2020). The following data concerns to the Brazilian wastewater scenario in 2018: produced municipal wastewater, 8.539 km^3 year^{-1}; collected municipal wastewater, 5.361 km^3 year^{-1}; treated municipal wastewater, 3.539 km^3 $year^{-1}$; not treated municipal wastewater, 7.2 km^3 $year^{-1}$; direct use of treated municipal wastewater, 0.0295 km^3 $year^{-1}$; and direct use of treated municipal wastewater for irrigation purposes, 0.008 km^3 $year^{-1}$ (Food and Agriculture Organization - FAO, 2021).

As the basic sanitation systems in Brazil are not sufficient to meet the sanitary requirements in the rural areas, an alternative system was developed by Brazilian Agricultural Research Corporation (Embrapa) to enable the treatment of domestic sewage, called biodigestor septic tank. There are more than 11,500 systems already installed in Brazilian rural properties and it consists basically of a biological treatment of sewage through fermentation digestion, using ruminant manure as an inoculating medium for anaerobic bacteria. The septic tank is generally formed by three 1,000 L tanks, connected in series by pipes and siphons. In the first two tanks, fermentation process takes place, while the third tank stores the treated effluent. The sewage which is treated in the system comes only from toilets (feces and urine) and is technically characterized as black water. The use of biodigestor sept tank minimizes the potential risk of groundwater contamination, pollution and the dissemination of human diseases. The treated sewage effluent (TSE) is rich in nitrogen and potassium, and with smaller amounts of phosphorus, calcium, magnesium, sulfur and organic matter, and can be applied as a fertilizer to the soil (Silva, 2014; Galindo et al., 2019).

Some benefits of wastewater use in agriculture include the reduction of water diversion costs; the value of a secure "droughtproof" water supply; the increase of farm production; and the value of wastewater nutrients whcih can imply in savings in chemical fertilizer applications (Anderson, 2003). Beside that, sewage sludge has also been used as source of nutrients for plants (Kepka et al., 2016). The collection, treatment and disposal of wastewater is of particular importance since it has an important role to play in water resources management as a substitute for fresh water in irrigation and other uses (Hamoda, 2004). Wastewater has been increasingly used in both developing and industrialized countries due to increasing water scarcity and stress, and degradation of freshwater resources resulting from improper disposal of wastewater; population increase and related increased demand for food and fiber; a growing recognition of the resource value of wastewater and the nutrients it contains; and the Millenium Development Goals (MGDs), especially the goals for ensuring environmental sustainability and eliminating poverty and hunger (World Health Organization - WHO, 2006). But the safe implementation of wastewater reuse practices is an important issue (Kamizoulis, 2008). The same attention must be addressed for municipal sewage sludge (Kepka et al., 2016). Wastewater use can reduce the water diverted for plants, which is important in regions of low water availability, and even for low-income growers or smallholder farms, which can make sewage treatment in rural areas more attractive (United States Environmental Protection Agency - USEPA, 2012). Then, wastewater is becoming recognized in several parts of the world as an asset to be exploited rather than a liability to be treated and disposed of to the environment.

Corn is the most produced cereal in the world, and Brazil is the third largest global producer and second largest global exporter (Federação das Indústrias do Estado de São Paulo - FIESP, 2021), due to two croping seasons carried throughout the year, i.e., in spring/summer time and after soybean cultivation as a rotation crop in summer/autunn time in South Hemisphere. But corn cultivation is also of great importance for Brazilian smallholder or family farming, which is characterized by low adoption of technology, i.e., absence of machines, breeder seeds, soil amendment and fertilizer, chemical inputs; by cultivation in small surface area and low number of workers; and by the use of corn for human consumption and animal feed (Cruz et al., 2011). Moreover, when corn harvesting produces a surplus it is sold or used as a bargaining with neighbors or cooperatives, since the latter represents the most direct and secure way to purchase some inputs (Machado; Fontanelli, 2014). It has been reported the benefits of using wastewater as a source of water and nutients for grain production or silage purposes as a way to remove suspended solids from environment, attending partially or totally the plant nutrient requirement and increasing corn productivity (Javarez Junior; Ribeiro; Paula Junior, 2010; Mok et al., 2014; Malafaia et al., 2016; Cakmakci; Sahin, 2021).

Furrow irrigation has been used for wastewater applications (Javarez Junior; Ribeiro; Paula Junior, 2010; Belaid et al., 2019; Liu et al., 2019; Khanpae et al., 2020; Cakmakci; Sahin, 2021). Furrow irrigation restricts any pathogens or pollutants aerial dispersion (Ait-Mouheb et al., 2020). Spray and sprinkler irrigation have the highest potential to spread contamination onto crop surfaces and affect nearby communities, since bacteria and viroses can be transmitted through aerosols (WHO, 2006). It may be undesirable to use secondary quality reclaimed water where irrigation equipment results in aerosols, particularly where the area under irrigation is adjacent to the property boundary (USEPA, 2012). Besides irrigation improves the household livelihood and welfare of smallholder farmers, furrow irrigation is a low-cost technology that smallholder can afford and once the irrigator has acquired some practice furrow irrigation is relatively easy to operate (Araujo; Costa; Mateos, 2019).

We hypothezed that the wastewater we called TSE applied through irrigation can replace completely the N mineral fertilizer required by corn crop cultivation in a smallholder farming. Hence, the purpose of this study is to investigate the corn crop responses to the use of TSE from a biodigestor septic tank as a fertilizer applied by short and closed-end furrow irrigation in souhteastern Brazil.

MATERIAL AND METHODS

Experimental site

A field experiment was carried out from October 2018 to February 2019 in the municipality of São Carlos, state of São Paulo, Brazil (21°57'13.77" S 47°51'16.54" W 873 m), which presents a dry winter (Cw) and hot summer (Cwa) (Alvares et al., 2013). Soil was classified as dystrophic Red Yellow Latosol (Sartorelli et al., 2007), which correponds to an Oxisol in U.S. Soil Taxonomy (Soil Survey Staff, 2014). The 0-0,2 m soil layer presents 31.5% of clay, 5.7% of silt and 62.8% of sand, and texture is classified as sandy clay loam. Soil chemical characteristics before the begining of experiment are shown in Table 1.

Corn sowing and plot design

Corn sowing was carried out on Oct 4, 2018, using the hybrid cultivar Pioneer P4285VYHR, with RR gene. This cultivar is adapted to highland cultivation (above 700 m altitude) and has dual aptitude for grain and silage production. Plots were 9.0 m long and 4.8 m wide (43.2 m^2), with six rows of plants spaced 0.8 m apart, and a distance of 0.2 m between plants (5 plants m^{-1} equivalent to 62,500 plants ha^{-1}). Experimental unit or useable area within the plot was 7.0 m long and 3.2 m wide (four central rows, 22.4 m^2).

Invasive plant and disease control

Invasive plants were contoled by one glyphosate application (rate of 3 L ha^{-1}) using a backpack sprayer at 33 *das* (days after sowing). No disease control was necessary throughout the growing season.

Irrigation system and management

A surface irrigation system (0.3 m wide, 0.15 m deep furrow between corn rows) was used. One 2" diameter PVC tube with five outlets spaced 0.8 m apart was used to delivery water into end-closed furrows. Water was pumped from a reservoir using a tractor power take-off (PTO) as energy source which provided a flow rate of 0.71 $m^3\ s^{-1}$. The same PTO and pump delivered TSE from another reservoir with the same flow rate into the furrows.

Soil field cacapcity (FC) and wilting point (WP) were 0.275 $m^3\ m^{-3}$ and 0.182 $m^3\ m^{-3}$, respectively, which provide a total available soil water (TASW) of 0.93 mm water cm $soil^{-1}$. Considering the upper 0.20 m depth, FC, WP and TASW correspond to 55.0 mm, 36.4 mm and 18.6 mm, respectively. Adopting the depletion fator (*f*) equal to 0.6, a reduction of 7.4 mm occurs, reaching a value of 47.6 mm as critical available soil water (CASW).

Irrigation management was based on the daily crop evapotranspiration (ETc, mm) which was obtained from the daily reference evapotranspiration (ETo, mm) provided by an automatic weather station placed at 21°57'42" S, 47°50'28" O, 860 m and 1,657 m far from experimental area. Rainfall was collected in a pluviometter installed closed to the plots. Crop coefficients (kc) used were 0.86 in phase 1, from sowing (Oct 4, 2018) to Oct 24, 20 *das*; 1.03 in phase 2, from Oct 25 to Nov 27, 21 to 54 *das*; 1.23 in phase 3, from Nov 28 to Jan 6, 2019, 55 to 94 *das*; and 0.97 in phase 4, Jan 7 to Feb 4, 95 to 123 *das* (Andrade; Albuquerque, 2015). Corn growth phases adopted were those proposed by Allen et al. (1998). Irrigation was performed when the sum of daily ETc reached or was close to 14.7 mm. When a rain occured, its magnitude was considered together ETc value to adjust irrigation water depth to be applied.

Soil water content (θ, $m^3\ m^{-3}$) in the upper 0.2 m depth was measured using a handheld TDR device previously calibrated in laboratory for this site soil. Measurements were taken inside the useful plot areas and in the end of the furrows since water distribution is critical at that point. Values of θ were multiplied by 200 mm to determine available soil water (mm).

Table 1: Soil chemical attributes at 0-0.2 m layer.

pH	o.m.	P	Al^{3+}	$H^+ + Al^{+3}$	K^+	Ca^{2+}	Mg^{2+}	BS[1]	CEC[2]	V[3]
$CaCl_2$	g dm^{-3}	mg dm^{-3}	---------- mmol$_c$ dm^{-3} ----------							%
5.1	25.08	9.5	0.75	26.75	2.71	21.75	10.25	34.75	61.58	56.58

o.m. - organic matter; [1]sum of bases; [2]cation exchangeable capacity, [3]base saturation = (BS/CEC). 100.

Fertilizer application and experimental design

Nutrient rates were calculated based on the soil chemical analysis and on corn´s fertilizer recommendation for the state of São Paulo (Raij et al., 1997). The mineral fertilizers used were urea, simple superphosphate and potassium chloride. Four treatments were evaluated in a randomized block design with three replications: side dressing application of N, P and K from mineral fertilizers; application of effluent (Ef) by fertirrigation and P and K from mineral fertilizers; application of Ef only; and application of P and K only (Table 2).

Sample of TSE was colected from the septic tank before the begining of experiment for analyses in laboratory using the multiple tube methodology (American Public Health Association - APHA, 2005). The results found were determined based on the most probable number (MPN). Total and thermotolerants (*Escherichia coli*) coliforms were 1.2 10^4 and 4.5 10^3 colony forming unit (CFU) 100 mL^{-1}, respectively. Plasma optical emission spectrometry was used for quantitative analysis of phosphorus and potassium while nitrogen was determined by Kjedhal method (Silva et al., 2012). For fertigation application, it was taking into account that TSE presented 339 mg of N L^{-1}, 7 mg of P L^{-1} and 67 mg of K L^{-1}. Its pH (H_2O) value was equal to 7.52.

Harvesting and evaluation of crop paramenters

Harvesting was performed on February 4, 2019. Fifity ears of corn were randomly collected in useable area of each experimenatl unit to determine mass of ear without straw (g), ear length (cm), ear diameter (apex, medium, base), grain length (apex, medium, base), number of grains per ear, number of rows per ear, average number of grains per row, mass of grains per ear (g) and mass of 1.000 grains. Ears were manually treshed and grain yield (kg ha^{-1}) was estimated by mass of grains per ear and the usable area of each plant (spacing between plants and between rows) at 13% moisture (yield = mass of grain per ear x 10.000 / plant usable area).

Grain size classification was performed using sieves with oblong screens (20, 17, 14, and 10.5). Grains removed from the bottom pan after passing through the sieves did not have any classification. Mass of grains retained in each sieve and in botton pan were determined on a precision scale and expressed in percentage of total mass of grains (Silva et al., 2008).

Leaf area index (LAI) was estimated from readings of 16 plants per plot using AccuPAR LP-80 ceptometer (Meter Group, USA), which measures light interception by leaves. Capture of photosynthetically active radiation (PAR) from 400 to 700 nm range was taken simultaneously by the device probe and the external point sensor placed below and above the canopy, respectively.

Statistical analysis

Data were submitted to analysis of variance (ANOVA). Plant attributes were submitted to F test at 1% and 5% significance levels. Data homogeneity and normality were analyzed by chi-square and Shapiro-Wilk tests, respectively, using the SPSS Statistic 16.0 software, while ANOVA and mean comparison test (Tukey's test) were performed using the SISVAR software. Regression analyzes and their level of significance were performed using an Excel spreadsheet.

Table 2: Nutrient rates and times of application of nitrogen, phosphorus and potassium[1] (NPK), TSE[2], phosphorus and potassium (EfPK), TSE (Ef), and TSE, phosphorus and potassium (EfPK).

	NPK			EfPK			Ef			PK	
	N	P	K	N	P	K	N	P	K	P	K
Sowing	23	121	50	23	0.5+118.2	4.7+46.2	23	0.5	4.7	121	50
24 *das*[3]	25	-	-	-	-	-	-	-	-	-	-
25 *das*	-	-	25	25	0.5	5+20	25	0.5	5	-	25
32 *das*	25	-		25	0.5	5+40	25	0.5	5	-	-
40 *das*	50	-	50	25	0.5	5	25	0.5	5	-	50
43 *das*	-	-	-	25	0.5	5	25	0.5	5	-	-
48 *das*	12	-	8.3	12	0.3	2.4	12	0.3	2.4	-	8.3
Total	135	121	133.3	135	121	133.3	135	2.8	27.1	121	133.3

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage efluent; [3]days after sowing.

RESULTS AND DISCUSSION

Irrigation and fertirrigation management

In Oct and Nov 2018, applications of water and TSE depths in EfPK and Ef treatments occured in seven days (11, 23, 30, 37, 44, 47 and 51 *das*) but four of them (11, 44, 47 and 51 *das*) were fulfilled only for TSE application while one water application (23 *das*) was made for all treatments and other two (30 and 37 *das*) were performed for TSE and water applications (Table 3). It is important to emphasize that N dose is recommended to be applied until V8 phase of corn plants (Randall; Vetsch; Huffman, 2003), which occured at 51 *das* (Nov 24, 2018). In Oct 2018, it rained 323.8 mm, and from this monthy value 160.4 mm rained from 12 to 22 *das,* and applications of TSE at 44, 47 and 51 *das* were followed by rains of 36.8 mm (45 *das*), 12.2 mm (46 *das*), 23.4 mm (49 *das*), 13.4 mm (50 *das*), 6.4 mm (52 *das*), 12 mm (53 *das*), 34 mm (54 *das*), 27.4 mm (55 *das*) and 5.3 mm (56 *das*) (Figure 1). Hence, in the first two months of corn´s growing season, application of irrigation water depth in NPK and PK treatments after four TSE applications to equal total (water + TSE) depth applied were not performed because of rain occurence. Consequently, NPK and PK received 77.1 mm from irrigation water, while EfPK and Ef treatments received 59.3 mm from irrigation water and 48.0 mm from TSE application, which leads to a differrence of 30.2 mm in total (water + TSE) depth (Table 3). Total ETc in Oct and Nov 2018 were 70.7 mm and 106.1 mm, respectively.

Table 3: Application of irrigation and treated sewage effluent (TSE) depths in treatments nitrogen + phosphorus + potassium (NPK); TSE + phosphorus + potassium (EfPK); TSE (Ef); and TSE + phosphorus + potassium (EfPK).

Month/ day	das[1]	NPK	EfPK		Ef		PK
		Water	Water	TSE	Water	TSE	Water
Oct 15	11			8.3		8.3	
Oct 27	23	22.0	22.0		22.0		22.0
Nov 3	30	32.7	23.8	8.8	23.8	8.8	32.7
Nov 10	37	22.4	13.5	8.9	13.5	8.9	22.4
Nov 17	44			8.9		8.9	
Nov 20	47			8.9		8.9	
Nov 24	51			4.2		4.2	
Dec 9	66	18.5	18.5		18.5		18.5
Dec 14	71	17.6	17.6		17.6		17.6
Dec 19	76	10.8	10.8		10.8		10.8
Dec 22	79	17.8	17.8		17.8		17.8
Dec 26	83	12.5	12.5		12.5		12.5

[1]Days after sowing.

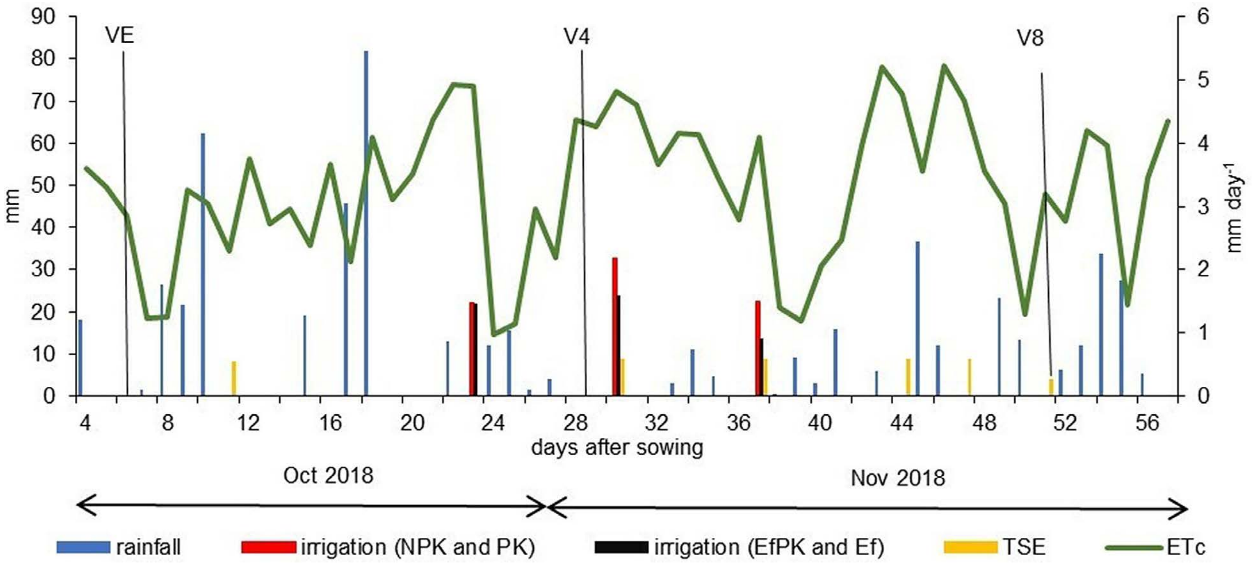

Figure 1: Crop evapotranspiration (ETc), rainfall (mm) and treated sewage effluent (TSE) and irrigation water depths applied in October and November, 2018 thorughout the phenological stages of emergence (VE), four fully expanded leaves (V4), and eight fully expanded leaves (V8) of corn plants.

In Dec 2018 irrigation depth applied in all treatments was 77.2 mm in five events (Table 3) and it rained 145.1 mm in that month while no irrigation was performed in Jan 2019 when it rained 154.0 mm well distributed over the time (Figure 2). Dec 2018 was the most critical crop period for plant water requirement since it was within the corn reproductive phase. In that month, the highest value of kc (1.23) was used, which resulted in an average value of ETc of 5.3 mm.day^{-1}. Monthly ETc values were 163.4 mm (Dec 2018) and 99.5 mm (Jan 2019). No irrigation or rainfall ocurred in Feb 2019 until the corn ear harvesting on Feb 4th.

Total rainfall during the corn growing season was 847.4 mm (323.8 mm in Oct 2018, 224.5 mm in Nov 2018, 145.1 mm in Dec 2018, and 154.0 mm in Jan 2019, which correspond to 38%, 29%, 17%, and 18% of total, respectively). Sixty seven percent of total rainfall was accumulated during the first two months of growing season, throughout the vegetative growth phase of corn.

Nevertheless, soil water content among treatments were very close each other at 0.20 m soil layer (Figure 3) because of high magnitude rains in Oct and Nov 2018 and Jan 2019 and of equal irrigation depth for all treatments in Dec 2018. Hence, difference of total (water + TSE) depth applied seems not to prejudice plant development. In the first two months soil water storage up to 0.20 m depth in all treatments remained between FC and CASW (Figure 4) while soil water available reduced a little even surpassing CASW in 3 days (65, 68 and 82 das) of Dec 2018 (Figure 5).

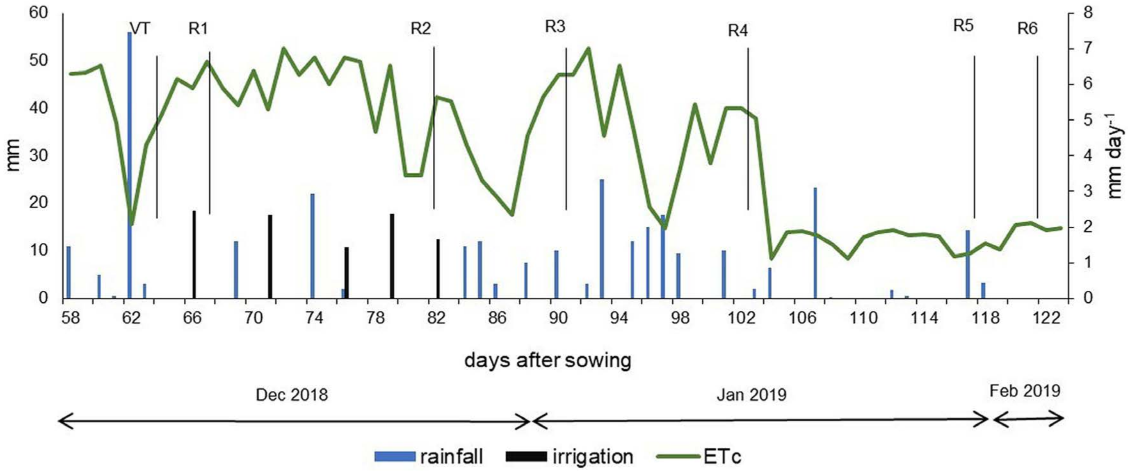

Figure 2: Crop evapotranspiration (ETc), rainfall (mm) and irrigation water depth in December 2018 (A) and January 2019 (B) in all treatments thorughout the phenological stages of tasseling (VT), silking (R1), blister (R2), milk (R3), dough (R4), dent (R5), and black layer – physiological maturity (R6).

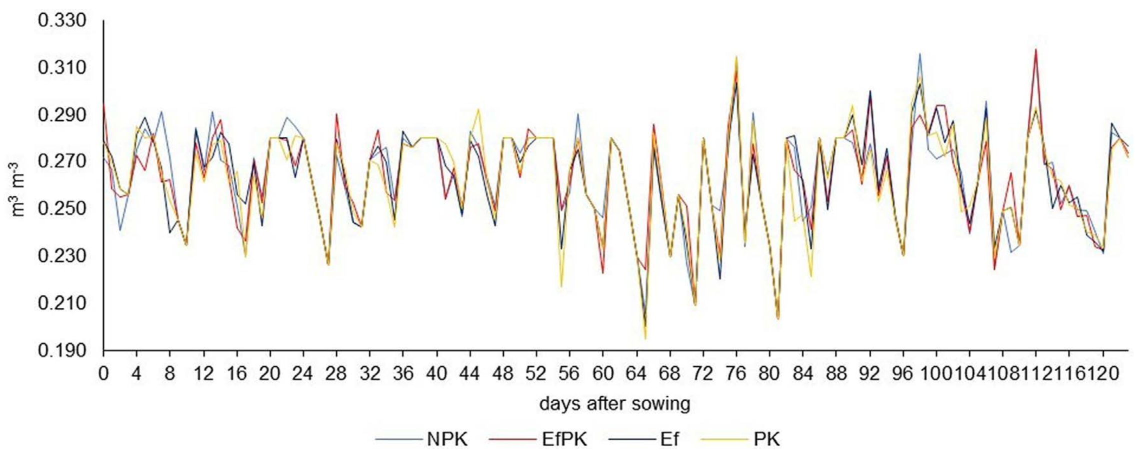

Figure 3: Soil water content at soil layer of 0.2 m measured by TDR device throughout corn growing season.

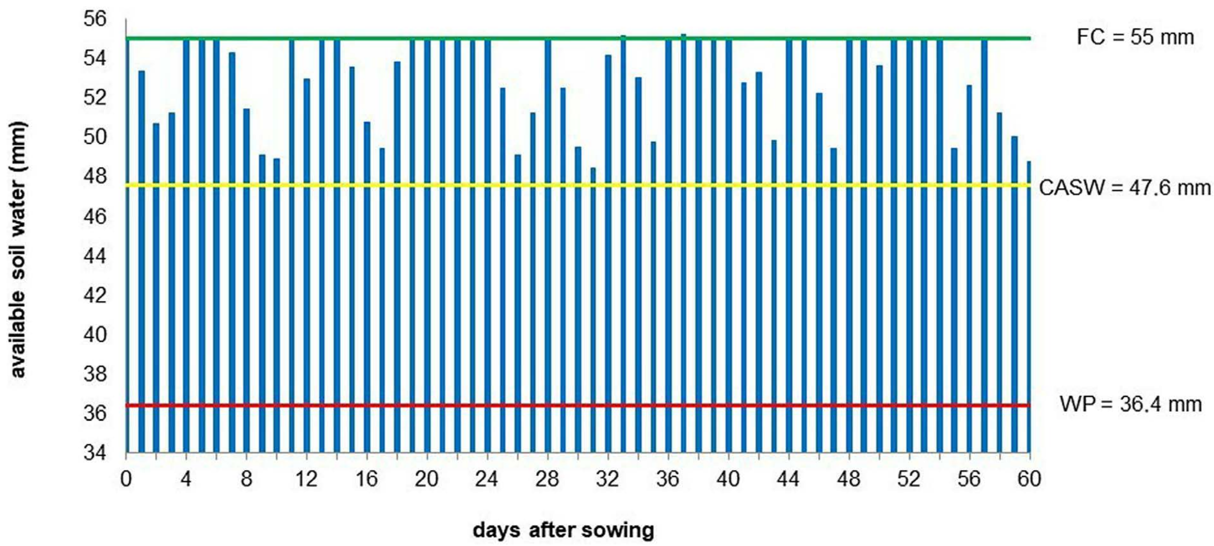

Figure 4: Soil water storage (mm) up 0.20 m depth in October and November 2018. Upper, middle, and bottom strips represent field capacity (FC), critical available soil water (CASW), and wilting point (WP), respectively.

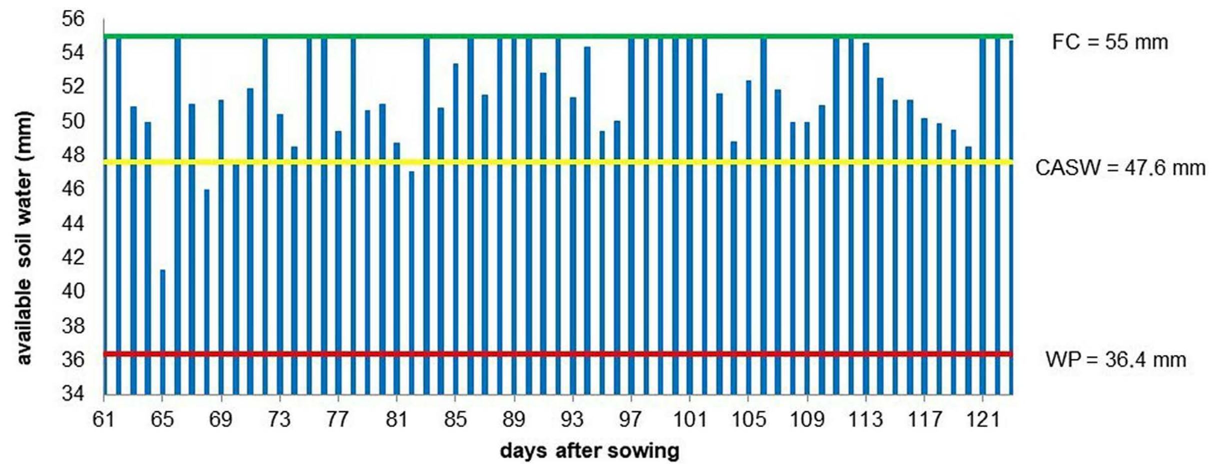

Figure 5: Soil water storage (mm) up to 0.20 m depth in December 2018 and January 2019. Upper, middle, and bottom strips represent field capacity (FC), critical available soil water (CASW), and wilting point (WP), respectively.

Responses of ear mass, grain mass, yield and mass of 1,000 grains

ANOVA for ear mass (g), grain mass (g), yield (kg ha^{-1}) and mass of 1,000 grains (g) resulted in a significant difference ($p<0.01$) among treatments. For all variables, NPK and EfPK treatments did not differ from each other, while EfPK did not differ from the Ef treatment for all variables either. However, Ef treatment was statistically different from results found in NPK plots. The highest yield values were found in NPK and EfPK, with 12,127.61 and 9,774.63 kg ha^{-1}, respectively (Table 4).

There are reports from Brazil about sewage use as a source of nutrients for plant growth. In a loamy/clayey-textured soil, similar corn yields were obtained with the use of sewage sludge to those obtained with the practice of mineral fertilization (Vieira; Moriconi; Pazionotto, 2014). Application of 50 m^3 ha^{-1} (118.5 kg of N ha^{-1}, 95 kg of P_2O_5 ha^{-1} and 65.5 kg of K_2O ha^{-1}) of treated swine effluent in a clayey soil obtained similar corn yield as with mineral fertilizer (urea, simple superphosphate and potassium cloride), and no yield increasing was observed beyond the rate of 91 m^3 of effluent per ha (Moraes et al.,

Table 4: ANOVA and Tukey's test of ear mass, grain mass, yield and mass of 1,000 grains, as function of application with nitrogen + phosphorus + potassium[1] (NPK), TSE[2] + phosphorus + potassium (EfPK), TSE (Ef), and phosphorus + potassium (PK).

Treatments	Ear mass (g)	Grain mass per ear (g)	Yield (kg ha^{-1})	Mass of 1.000 grains (g)
NPK	306.24 a	194.04 a	12.127.61^{a}	401.56 a
EfPK	253.44 ab	156.39 ab	9.774.63 ab	376.62 ab
Ef	198.71 b	121.98 b	7.623.75 b	344.93 bc
PK	124.30 c	70.08 c	4.379.83 c	339.85 c
Treatment	18166.45**	8326.27**	32525560**	2504.64**
Block	227.73^{NS}	117.35^{NS}	458115^{NS}	189.91^{NS}
Error	331.25	115.02	449308	65.42
C.V. (%)	8.25	7.91	7.91	2.21
Average	220.67	135.62	8.476.45	365.74

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage effluent; **, * and NS means significant at 1% and 5% level probability and not significant, respectively, by the F test. Values in the columns followed by the same letter did not differ from each other by Tukey's test (p<0.05).

2014). The application of sewage sludge biochar (SSB) alone and together with NPK in a clayey texture soil increased corn yield compared to control (without SSB and without fertilizers), but no differences were found between both (Figueiredo et al., 2019). Irrigation with swine wastewater diluted to 50% in soils with medium texture (Red-Yellow Oxisol) and clayey texture (Red-Yellow Ultisol) increased the levels of N, K, Ca, Mg and Zn in the aerial part of corn (Cunha et al., 2021). Futhermore, industrial saline wastewater application (0, 10, 20, 40 and 60 m^3 ha^{-1} year^{-1}) in a corn-soybean rotation on an Oxisol significantly increased corn (all rates) and soybean (only with the highest rate) yields around 103 -250% and 50%, respectively, in comparison with no wastewater application, but the use of high rates of that wastewater could cause soil salinization (Fink et al., 2021). In Australia, silage maize and sweet corn were grown with municipal and industrial wastewater irrigation compared to freshwater irrigation with and without fertilizer. Both harvests produced yields and qualities comparable to comercial farm standards, and no significant yield differences were found between water types. Wastewater can be viably used as agricultural irrigation water with no significant crop yield or quality losses and both sweet corn and silage maize have been shown to be suitable crop candidates for wastewater irrigation (Mok et al., 2014). In Turkey, in a sandy clay soil, increasing application rates of treated sewage sludge (TSS) resulted in significantly increase of total biomass and grain yield of corn, but grain yield of wheat (second crop in a rotation production system) did not change significantly (Deliback; Ongun, 2016). Those authors recommended the rate of 37.5 ton of TSS ha^{-1} in a two years period.

Higher yield values were observed in treatments in which TSE was applied (EfPK and Ef) in comparison with no TSE application (PK treatment). This behavior was also reported by Chandrikapure et al. (2017) and Elamin et al. (2019), i.e., higher yield with TSE applications throughout the growing season compared with irrigation water application only. Thus, the replacement of mineral nitrogen by organic nitrogen can be performed without reducing corn crop yield.

Nitrogen is a nutrient of great importance for plants since its adequate supply contributes directly or indirectly for the content of proteins, stability and polarization of cell membrane, water and nutrient uptake, stomatal regulation, lipid biosynthesis, photosynthesis and biomass production; however the absence of nutrients such as phosphorus and potassium impair processes such as root growth, maintenance of leaf water potential, cell turgidity and stomatal conductance, water and nutrient uptake and assimilation, and photosynthesis, which affects plant development (Waraich et al., 2011). Analysis of fifty years of field experiments demonstrated that N and P fertilization has a strong positive interaction on corn yield (Schlegel; Havlin, 2017). A five years long experiment has reported that adequate fertilization with both N and K optimize corn grain yield and allow corn to express its response potential. A K deficiency reduced yield for applied N rates as well as reduced the corn capacity to respond to N fertilization (Mallarino; Hirmiak; Oltmans, 2018). This can be proven by the Ef treatment which received the same nitrogen rate but did not result in yield equal to that of NPK, since soil experiment presented low and medium contents of P and K, respectively (Raij, 1997). Plants that have a greater absorption of nutrients have greater yield, since process of production and translocation of photoassimilates to the grain are greater (Ferreira et al., 2001).

NPK and EfPK yields of corn grains were higher to those of Brazilian states that historically have high average yields, such as states of Goiás and Paraná, which in the summer growing season reached 9,000 and 8,373 kg ha^{-1}, respectively (Companhia Nacional de Abastecimento - CONAB, 2021). The relatively high yield values achieved in this study can be explained by adequate crop fertilization, rainfall distribution throughout crop season and irrigation use.

PK treatment obtained the lowest values for ear and grain mass. Values of average grain mass and mass of 1,000 grains did not differ from Ef and EfPK treatments, but differed from NPK. Fertigation with primary sewage resulted in higher values of plant height, stem diameter, number of leaves, husked ear weight, ear weight without straw, wet and dry grain weight and grain yield compared to the same characteristics when artesian well water was used (Costa et al., 2014). Corn ear mass increases with N rate increasing (Ashraf et al., 2016). Corn plants fertilized with effluent originated from cassava processing (high K content) and supplemented with N and P produced similar ear dry mass (with and without straw) and grain mass to the plants fertilized with mineral NPK application (Araújo et al., 2019).

Highest mass of 1,000 grains was obtained in NPK and EfPK treatments (Table 4). Grain mass depends directly on the crop N supply, because it is formed by proteins, which present amino acid chains in its constitution and are dependent on N to be formed (Below, 2002). The values reported herein were higher to those obtained by Andrade et al. (2014), Kappes et al. (2014) and Batista et al. (2020). All of them used 150 kg N ha^{-1} rate in corn and found 256.0, 345.1 and 338.1 g of grain mass, respectively. Khan et al. (2014) used rates of 150 kg N ha^{-1} and 100 kg P_2O_5 ha^{-1} in three maize varieties and reached a highest ear weight of 449g. Mousavi and Shahsavari (2014) observed a greater mass of 1,000 grains with TSE application than with only irrigation water application.

Responses of ear diameters and grain lengths

ANOVA of ear diameters and grain lengths showed that a significant difference ($p<0.01$) occured among treatments (Table 5).

Ear diameter at apex was higher in NPK treatment. Ear diameter at middle and bottom parts were equal in NPK and EfPK treatments, proving that N use from TSE allows obtaining values equal to those from plants which received mineral fertilizer. No diferences were found between Ef and EfPK. P and K not supplied to corn crop reduced ear diameter. On the other hand, PK treatment presented statistically equal values to those from Ef, but differed from NPK and EfPK by N absence and leaded this treatment to the smallest ear diameters (Table 5).

Table 5: ANOVA and Tukey's test for ear apex diameter (EAD), ear middle part diameter (EMD), ear bottom diameter (EBD), apex grain length (AGL), middle part grain lengtht (MGL) and bottom grain length (BGL), as function of application of nitrogen + phosphorus + potassium1 (NPK), TSE2 + phosphorus + potassium (EfPK), TSE (Ef), and TSE + phosphorus + potassium (EfPK).

Treatments	EAD (mm)	EMD (mm)	EBD (mm)	AGL (mm)	MGL (mm)	BGL (mm)
NPK	36.01 a	47.94 a	51.15 a	7.09 a	10.56 a	11.07 a
EfPK	33.64 b	46.72 ab	49.23 ab	6.34 ab	10.29 a	10.47 ab
Ef	32.63 b	45.22 bc	47.09 bc	6.72 b	10.28 a	9.98 b
PK	30.07 c	43.23 c	43.91 c	5.12 c	9.41 b	9.05 c
Treatment	18.17**	12.34**	28.93**	2.19**	0.75**	2.18**
Block	0.81^{NS}	0.76^{NS}	0.74^{NS}	0.09^{NS}	0.02^{NS}	0.03^{NS}
Error	0.11	0.38	0.94	0.12	0.01	0.03
C.V. (%)	0.98	1.35	2.03	5.36	1.28	1.92
Average	33.08	45.77	47.84	6.31	10.14	10.14

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage effluent; **, * and NS means significant at 1% and 5% level probability and not significant, respectively, by the F test. Values in the columns followed by the same letter did not differ from each other by Tukey's test ($p<0.05$).

Highest grain lengths at ear´s apex and bottom were found in NPK and EfPK, and at ear´s middle part, in NPK, EfPK and Ef. Lack of N reduced the values from PK treatment in ear´s middle part. The greatest difference took place at ear´s bottom where greatest grain lengths were achieved in NPK and EfPK treatments (Table 5).

Application of treated swine effluent and mineral fertilizer did not produce diferences on cor ear diameter (Moraes et al., 2014) and those results weere similar as we have reported herein. As the application of treated municipal wastewater incresed, an increasing of ear diameters from 20 mm to 25 mm was observed (Mousavi; Shahsavari, 2014). Ear diameters of 21.7, 24.3, 26.6 and 29.2 mm were obtained with 0, 150, 200 and 250 kg N ha^{-1} rates, respectively (Ashraf et al., 2016). In our study, supply of 135 kg N ha^{-1} produced mean values of ear diameter between 46.72 and 47.94 mm (ear middle part) and 49.23 and 51.15 mm (ear bottom part) in NPK and EfPK treatments.

A highly positive and significant correlation (*p<0.01*) was observed between ear diameter and grain yield, and among ear diameter at bottom and middle parts with yield (Figure 6). Ear diameter directly influences grain yield as it is related to grain mass per ear (Lopes et al., 2007).

In all grain lengths measured there was a positive and significant relationship with yield however a better linear regression adjustment and greater *R* and *r* values was found for ear bottom diameter (EBD) which indicates that the variations in yield is highly associated with variations in the grain length at this part of the ear (Figure 7). Higher correlation between yield and ear bottom diameter happens because these grains are larger and heavier than grains formed in ear´s apex and middle part (Batistella Filho; Moro; Carvalho, 2002).

Responses of ear length, number of rows, number of grains and avegrage number of grains per row

Corn ear length varied significantly (p<0.001) among treatments (Table 6) and the highest values occurred in the NPK and EfPK treatments. Corn ear lenghts of 16 cm (Kappes; Arf; Andrade, 2013) and 13.6 cm (Gazola et al., 2014) at a rate of 120 kg N ha^{-1} have been reported. Application of treated swine effluent (118.5 kg ha^{-1}) and urea (110 kg N ha^{-1}) produced ear length of 16.5 cm (Moraes et al., 2014). Applications of only TSE and 25% of water plus 75% of TSE in all stages of corn crop achieved ear lengths of 18.63 and 18.55 mm, respectively (Mousavi; Shahsavari, 2014). In greenhouse conditions, 17 cm ear long was obtained with an appllication of 200 kg N ha^{-1} using cassava wastewater as TSE source while 13 cm ear long was observed with urea fertilization (Araújo et al., 2019). Hence, TSE can be used as a nutrient source since it was obtained corn earn lengths similar to those from mineral fertilization application.

A crop nutritional deficiency generates ears with shorter lengths as it is seen in the Ef treatment which received the same dose of N as the NPK treatment and produced smaller ears. Nitrogen is a nutrient of great importance for the development of corn ears but the absence of other nutrients limits its action (Oktem; Oktem; Emeklier, 2010; Amanullah et al., 2016; Foncha et al., 2019). In PK treatment the absence of N generated an even greater reduction in ear length. The values for Ef and PK were 14.61 and 10.97 cm, respectively. Meanwhile, NPK and EfPK treatments with lengths of 18.92 and 18.76 cm, respectively.

Corn ear length has a positive relationship with the number of grains per ear and consequently with grain yield (Figure 8) which has been reported by previous studies (Lopes et al., 2007; Sartor et al., 2012; Kappes; Arf; Andrade, 2013).

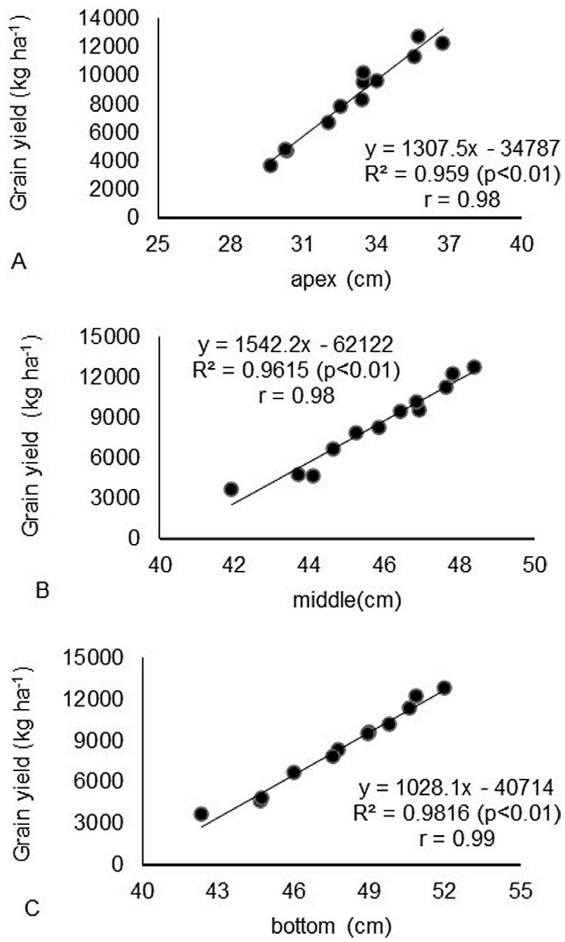

Figure 6: Grain yield as function of ear diameter at apex (A) middle (B) and bottom (C) parts.

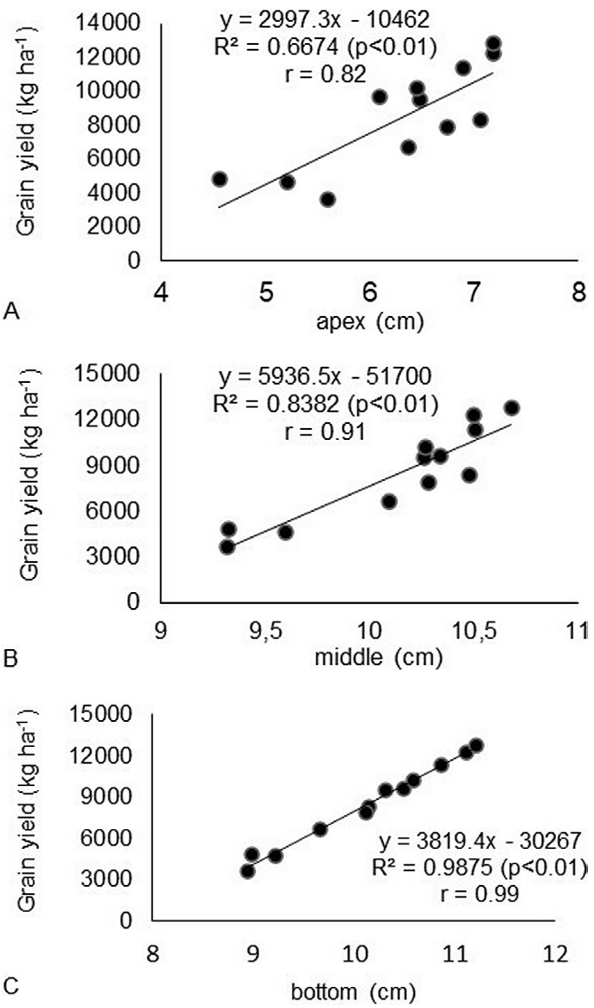

Figure 7: Grain yield as function of grain length at apex (A), middle part (B) and bottom (C) of corn ear.

NPK and EfPK treatments presented higher number of grains per ear and average number of grains per row while only PK treatment presented a significantly lower number of rows per ear than others (Table 6). TSE application without P_2O_5 and K_2O reduced the number of grains per corn ear by 26.63% compared to NPK treatment. However a greatest reduction occurred in PK treatment without N application (56.92%) evidencing the importance of this nutrient for this crop. Corn responds to application of increasing N rates with increasing yield components (Melo; Corá; Cardoso, 2011; Araújo; Vitorino; Mercante, 2016). Rate application of 150 kg N ha^{-1} reached a range of 400 and 500 grains per ear in three corn varieties (Khan et al., 2014) or 424 grains per ear and 31 grains per row (Ashraf et al., 2016).

Number of grains and average number of grains per row have a positive correlation with grain yield (Figure 9). Both presented significant regressions (*p<0.001*) and high Pearson's correlation index. As in ear length, the increment of number of grains can mean an increase of grain yield.

Percentages of the total mass of corn grains in the 20, 17, 14 and 10.5 sieves and in the botton pan showed significative difference among treatments (Table 7). The percentual values of retained mass of grains increased as sieve diameter reduced, and grains which were not sorted and retained in the botton pan represented less than one percent. NPK presented higher values in all sieves, but those values did not differ from PK in 17 sieve, from Ef and PK in 14 sieve, and from EfPK and Ef in 10.5 sieve. More than 50% of total mass of grains for all treatrments were found in the sieve with lowest diameter. As PK treatment produced a smaller number of grains per ear there was more space for the grains to increase their size (Figure 10).

Grains of 10.5 sieve are of great importance for crop yield and are more desirable for mechanical harvesting and processing. Despite the smaller size those grains had a higher average mass of grain and mass of 1,000 grains meaning a greater dry matter accumulation. Zucarelli et al. (2014) also reported highest value of corn grains retained in the in 10 sieve.

LAI response

A significant effect (*p<0.001*) among treatments was observed for LAI measurements (Table 8). PK value differed from those of NPK and EPK but it was statistically equal to Ef. Treatments with the two highest IAF values presented greater ear lengths, average numbers of grains per row, numbers of grains per ear, ear weights, and grain yields. Higher plant density and higher LAI were correlated with higher values of ear parameters because they have a greater capacity to capture solar energy which provides greater energy conversion and greater biomass production (Sangoi et al., 2011). Soil with high water storage favors the N uptake by plant contributing to biomass production and increasing the crop's LAI (Wang et al., 2017). Greater LAI measurements were obtained in TSE irrigated corn plants when compared with those only irrigated with Nile river water (Elamin et al., 2019), as well as higher N rates and water depths increase corn LAI (Campelo et al., 2019). This was also observed in this work with NPK, EfPK, and Ef which received the same N rate and reached the highest LAI values.

Table 6: ANOVA and Tukey test of ear length, number of rows, number of grains and avegrage number of grains per row as function of application of nitrogen, phosphorus and potassium[1] (NPK), TSE[2], phosphorus and potassium (EfPK), TSE (Ef), and TSE, phosphorus and potassium (EfPK).

Treatments	Ear lenght (cm)	Number of rows	Number of grains per ear	Average number of grains per row
NPK	18.92 a	14.11 a	486.95 a	34.65 a
EfPK	16.76 ab	14.09 a	427.23 ab	30.36 ab
Ef	14.61 b	14.04 a	357.51 b	25.45 b
PK	10.97 c	13.17 b	209.75 c	15.86 c
Treatment	34.48**	0.61**	42788.12**	195.45**
Block	0.33NS	0.02NS	450.43NS	2.12NS
Error	0.33NS	0.02NS	450.43NS	2.12NS
C.V. (%)	4.44	1.25	7.41	6.59
Average	15.31	13.85	370.36	26.58

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage effluent; **, * and NS means significant at 1% and 5% level probability and not significative, respectively, by the F test. Values in the columns followed by the same letter did not differ from each other by Tukey's test (p<0.05).

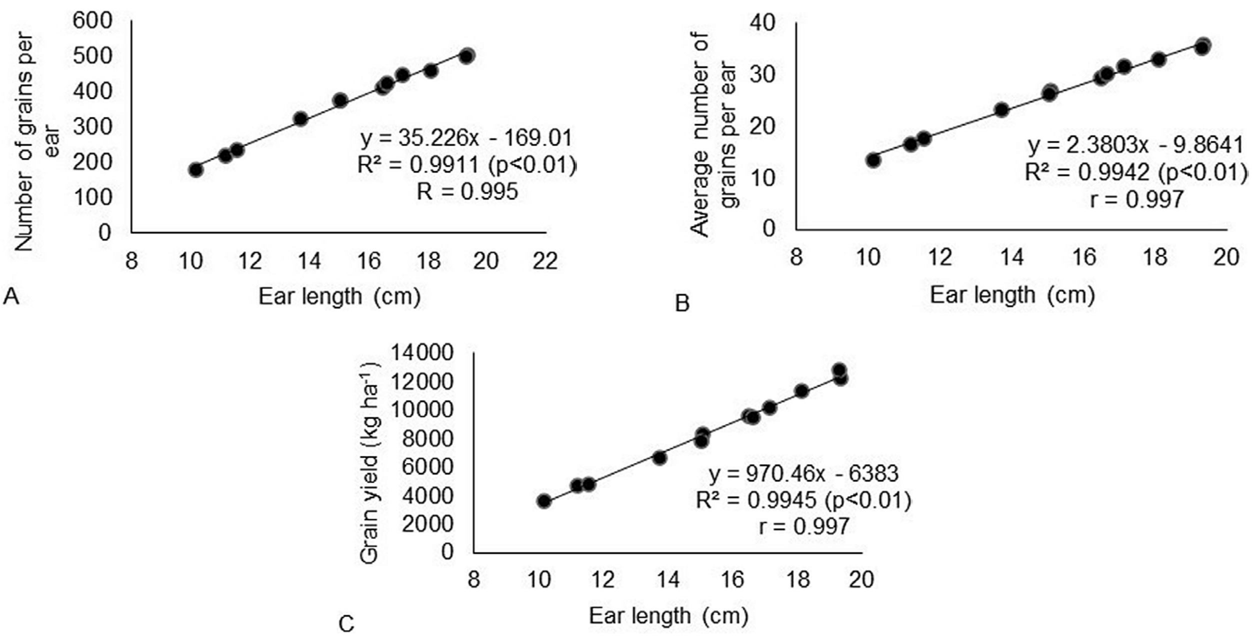

Figure 8: Number of grains per ear (A), number of grains per row (B), and grain yield (C) as function of corn ear length.

Greater interception of solar radiation provided by plants with greater IAF lead to a greater energy use in photosynthesis which provides greater photoassimilates production and dry matter accumulation, which increase parameters measured in a corn ear (Cruz et al., 2008). Half of carbohydrates destined to grains during reproductive phase originate from the upper part of corn leaves and stem which enphatize the importance of obtaining a high LAI (Fornasieri Filho, 2007). Higher LAI measured during corn flowering contributed to higher plant yields when compared to those with a lower index (Adebo; Olaoye, 2010; Sangoi et al., 2011).

A positive and significant relationship (*p<0.005*) among LAI and ear length, ear mass and grain yield (Figure 11) was observed. Increasing caused by LAI in ear parameters influences crop yield as larger amount of grain appears in a bigger ear.

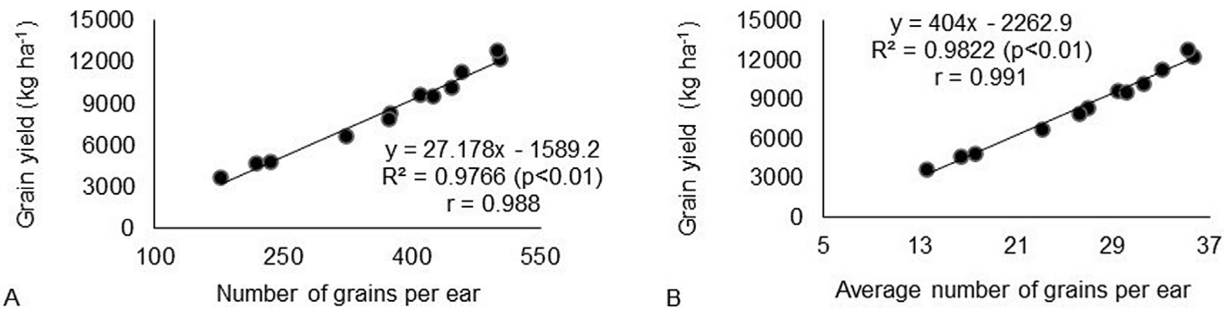

Figure 9: Grains yield as function of number of grains per ear (A) and average number of grains per ear (B).

Table 7: ANOVA and Tukey test for grain classification according 20, 17, 14, and 10.5 sieves and bottom as function of applications of nitrogen, phosphorus and potassium[1] (NPK); TSE[2] and phosphorus and potassium (EfPK); TSE (Ef); and phosphorus and potassium (EfPK).

Treatments	20 sieve (%)	17 sieve (%)	14 sieve (%)	10.5 sieve (%)	bottom (%)
NPK	2.54 a	9.04 ab	28.20 ab	60.05 ab	0.17 b
EfPK	1.22 b	6.94 b	24.38 b	67.25 a	0.21 b
Ef	1.20 b	6.58 c	31.56 ab	60.43 ab	0.23 ab
PK	0.82 c	11.87 a	35.98 a	51.04 c	0.29 a
Treatment	1.70**	15.77*	72.75*	132.58*	0.007**
Block	0.002^{NS}	5.03^{NS}	4.35^{NS}	2.08^{NS}	0.0008^{NS}
Error	0.005	2.13	10.67	17.46	0.0003
C.V. (%)	4.90	17.09	10.86	7.00	7.76
Average	1.45	8.54	30.08	59.70	0.22

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage effluent; **, * and NS means significant at 1% and 5% level probability and not significative, respectively, by the F test. Values in the columns followed by the same letter did not differ from each other by Tukey's test (p<0.05).

Figure 10: Corn ears from NPK, EfPK, EF and PK treatments, respectively, from left to right.

Table 8: Tukey test for leaf area index (LAI) as function of applications of nitrogen, phosphorus and potassium[1] (NPK); TSE[2] and phosphorus and potassium (EfPK); TSE (Ef); and phosphorus and potassium (EfPK).

Treatments	NPK	EfPK	Ef	PK
LAI	3.69 a	3.58 a	3.07 ab	2.31 b
Treatment	Block	Error	C.V(%)	Average
1.20**	0.07^{NS}	0.06	7.65	3.16

[1]Sources were, respectively, urea, simple superphosphate, and potassium chloride; [2]treated sewage effluent; NS, ** and * mean respectively not significant and significant at 1% and 5% by F test. Values in row followed by same letter do not differ by Tukey test (p<0.05).

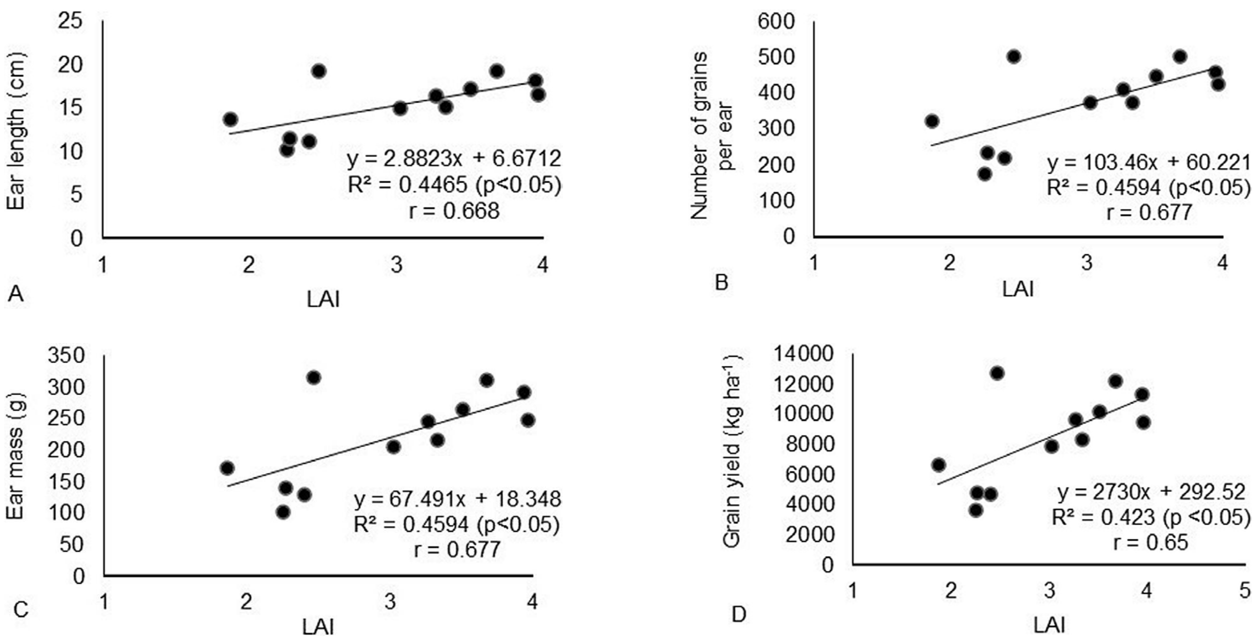

Figure 11: Ear length (A), number of grains per ear (B), ear mass (C), and grain yield (D) as function of leaf area index (LAI).

CONCLUSIONS

In southeastern Brazil, we evaluated in one growing season of a furrow irrigated corn crop the application of: NPK from mineral fertilizers; N from treated sewage effluent (TSE) together PK from mineral fertilizers (EfPK); TSE only; and PK only. Both NPK and EfPK applications promoted similar effects on yield paramenters (mass of ear and of grains; number of rows, grains per ear and grains per row, ear and grain sizes, and mass and size of grains) and LAI. Some yield parameters of corn were positively related to each other. Moreover, the corn LAI could be appointed as a proxy to estimate mass and lenght of ear, number of grains per ear and grain yield due to their directly proportional relationships. TSE can be a source of nitrogen and other nutrients for corn crop replacing mineral source of N mainly.

AUTHOR CONTIBUTIONS

Conceptualization: Abreu, P.A.S.; SILVA, W.T.L.; Bassoi, L.H.; Methodology: Abreu, P.A.S.; Costa, B.R.S.; Oldoni, H.; Silva, W.T.L.; Bassoi, L.H.; Formal analysis and investigation: Abreu, P.A.S.; Costa, B.R.S.; Oldoni, H.; Silva, W.T.L.; Bassoi, L.H.; Writing: Abreu, P.A.S.; Costa, B.R.S.; Oldoni, H.; Silva, W.T.L.; Bassoi, L.H.

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