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Proceeding

Agroecological fertilisation practices to improve sustainability and circularity in maize crop systems †

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Abstract: Agroecological practices, such as organic fertilisation offer a sustainable approach to crop systems. In this research, organic fertilisers made from a mixture of *nejayote* (lime-water) and ovine manure were evaluated in maize. Several indexes and indicators were calculated based on field data. The results demonstrated that *nejayote*-manure fertilisers improve Soil Quality (SQI=14.1), enhance efficiency in nutrient utilisation (Increased Yield, IY= 4.2 Mg ha^{-1}) and promote greater production biomass compared to chemical fertilisation. Organic fertilisations reduced dependency on external inputs and non-renewable energy, increased sustainability in maize, and facilitated the closure of nutrient cycles by integrating livestock, crop and agro-industrial systems.

Keywords: *Zea mays* L.; sustainability; circularity; soil quality, waste management

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1. Introduction

Agroecosystems sustainability is affected by their biological, agronomic, and economic productivity [1]. Productivity depends on soil quality, because of that, management practices should be directed towards reducing or preventing soil degradation [2,3]. Soil is crucial for human development, especially for rural populations that rely on agriculture for subsistence and poverty alleviation [4]. Small-scale farmers face various challenges in production, including limited economic resources and poor soil fertility. For the maize agroecosystem, macronutrient deficiency is one of the major yield limitations [5]. Therefore, soil management is critical to maximize nutrient use efficiency [6] and is essential for improving the sustainability of agroecosystems [4,7].

Intensive agriculture systems have moved away from circularity due to factors such as the specialization of production units and the substitution of organic sources of fertilization with chemical ones [8]. These systems demand a significant amount of energy from non-renewable sources and generate considerable amounts of waste. One option for achieving the transition towards circular and sustainable systems is the recycling of agricultural, livestock, and agro-industrial waste. In Mexico, the agro-industrial process of maize to produce tortillas and nixtamalized flours generates a contaminating waste called *nejayote*. This residue can be mixed with manure to produce organic fertilizers that offer several benefits in the maize agroecosystem such as costs reduction and increased yield [9]. In this research, two organic fertilizers derived from mixtures of *nejayote* and ovine manure were tested to determine their impact on soil quality, sustainability, and circularity in the maize agroecosystem. The study aimed to assess whether the application of *nejayote*-manure organic fertilizers results in differences in soil quality and the sustainability of yield, and to evaluate the differences generated by the treatments in the circularity of the system through biomass production, nutrient use efficiency, and the distribution of the energy utilized in the production process.

2. Materials and Methods

Research was done in Ahuazotepec, Mexico, during two cropping cycles (Spring-Summer 2015 and 2016). The experimental plot was located at 2268 masl and coordinates 20°01′51.6″ N and 98°07′15.6″ W. Climate was temperate and humid C(m). Two organic fertilisation treatments were evaluated for two maize production cycles. Organic fertiliser combinations of *nejayote* (lime-water) and ovine manure were prepared (OF1 = 75 m^3 ha^{-1} *nejayote* + 50 t ha^{-1} ovine manure, OF2 = 150 m^3 ha^{-1} *nejayote* + 50 t ha^{-1} ovine manure). Additionally, an unfertilised treatment (C) and a chemical fertilisation treatment (CF= 120N - 60P – 30K) were established for comparison. Treatments were arranged in randomised blocks with three replicates per treatment. Each experimental unit consisted of six rows with a net plot area of 48 m^2. The maize hybrid AS-722 (Aspros™) was planted on each unit using a sowing density of 75000 plants per ha. Fertilisation was applied manually on days 20, 40 and 60 after sowing on each cycle. Soil samples were taken before the start of the trial (Baseline: April 20, 2015) and after the first and second harvests (Cycle 1: November 10, 2015, and Cycle 2: December 10, 2016). A grid sampling method was used, soil samples (30 cm depth) were collected from the centre of each grid. For each sample different physical and chemical properties were measured as mentioned in [10].

2.1. Sustainability and circularity assessment

2.1.1. Soil Quality Index (SQI)

This index was calculated using the weighted additive model [11] showed in (1).

$$\text{SQI} = \Sigma_{i=1}^{n} w_i s_i, \quad (1)$$

where w_i= weight of the indicator and s_i=indicator score. An analysis of variance was performed for the total soil parameters available dataset to select those that generated statistical differences in maize yield ($P<0.05$). The selected indicators were loam content, OM, pH, cationic exchange capacity (CEC), EC, AN, AP, and AK. A Principal component analysis (PCA) for the selected indicators was used. In each PC the soil indicators with the largest absolute value were included in the Soil Quality Index (SQI). The weights of the indicators were obtained dividing the proportion of the variability explained by the PC by the total variability of the selected components. Each selected indicator was scored.

2.1.2. Yield and biomass

Sustainable Yield Index (SYI) [12]was estimated using (2):

$$\text{SYI} = [(\bar{y} - \sigma)/y_{max}] * 10 \quad (2)$$

where $\bar{y}$= mean yield of treatment, y_{max}= maximum yield obtained in the experiment (15.1 Mg ha^{-1}), and σ is the standard deviation of the experiment (2.7). Obtained values were multiplied by 10 to have a simpler scale. BP_{Food} and BP_{Feed} reflect the food and feed production, were estimated using biomass production data. For BP_{Food}, grain production was converted to nixtamalized flour yield, since this is the basis for many foods in the study area, and then production of protein was estimated using the chemical composition of flours reported by [13]. For BP_{Feed}, the production of maize stover was estimated from field data and protein production was calculated using a reference value of 3.9 % DM [14].

2.1.3. Nutrient cycling efficiency

To assess the nutrient cycling efficiency of the system the increased yield (IY) due to the applied fertilizer [15] was calculates as the difference between each treatment yield and control yield.

2.1.4. Energy consumption in maize production

Energy consumption used in maize production was estimated using energetic equivalents of the inputs and outputs as described in [9]. Inputs were grouped as Direct Energy (DE, human labour, and fuel), Indirect Energy (IDE, machinery, seed, chemical fertiliser, manure and *nejayote*), Renewable Energy (RE, seed, human labour, manure, and *nejayote*), and Non-Renewable Energy (NRE, fuel, chemical fertiliser, machinery, and herbicide) [16–18].

2.2. Statistical analysis

Statistical treatment of indicators and indices was performed using ANOVA and a Tukey test to compare means, effects were considered significant at $P<0.05$. All procedures were doing using Minitab 17 (Minitab Inc., State College, PA, USA).

3. Results

Sustainability and circularity assessment

Soil Quality Index (SQI)

SQI was then calculated substituting the scored means in (3). Weights for each principal component were PC1=0.421, PC2=0.343 and PC3=0.236, those values were assigned to the selected soil indicator in each PC.

$$SQI = 0.421(pH + CEC + EC + AP) + 0.343\ (AN + AK) + 0.236\ (OM) \quad 3)$$

Results for SQI ca be seen in **Figure 1**. Baseline values for SQI showed no differences ($P=0.944$). After Cycle 1, SQI increases in all treatments between 1.3 and 12.7% with respect to the baseline ($P=0.926$). For Cycle 2, the fertilization with OF2 increases SQI 12.9% with respect to CF, and 19.2% with respect to C ($P=0.03$). After two cropping cycles soil quality decreases 3.2 and 11.5% with CF and no C, respectively. On the other hand, OF2 and OF1 increase soil quality between 5.4 and 10.9% in the same period.

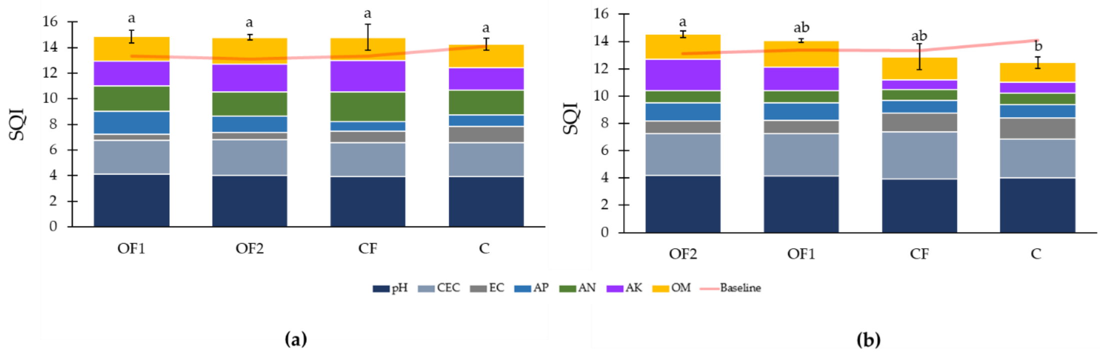

Figure 1. Soil quality indexes (SQI) of different fertilisation treatments applied to maize in Mexico; (a) Cycle 1; (b), Cycle 2; red line is the baseline value. Stacked bars showed the scored and weighed parameters used for SQI. Different letters indicate significant differences with Tukey method and a significance level $\alpha=0.05$. CEC, cation exchange capacity; CE, electrical conductivity; AP available phosphorus; AN available nitrogen; AK available potassium; OM, soil organic matter.

Yield and biomass

Sustainable Yield Index (SYI) had significant differences in both cycles ($P<0.05$). In cycle 1, SYI with OF1 and OF2 was 31.9% higher than C (**Figure 2**). For cycle 2, a generalised decrease in yield caused by Hurricane Earl affected SYI values (**Figure 2**). Even in those adverse climatic conditions, the yield of treatment OF1 was 58.9% more sustainable than that obtained with CF. It could be explained by a positive effect in soil quality due to the organic fertilisation (**Figure 1**).

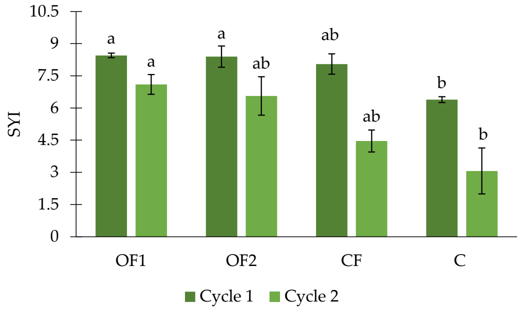

Figure 2. Sustainable Yield Index (SYI) for two maize production cycles under different fertilisation treatments in México. Different letters indicate significant differences with Tukey method and a significance level α=0.05.

An important ecosystem service of the soil is the production of edible biomass. BP_{Food} showed significant differences caused by the fertilisation treatment in both production cycles ($P<0.05$). CF and OF1 produced the higher protein yield in nixtamalized flour per hectare, 41.7 and 39.7% higher than control, respectively (**Table 1**). In cycle 2, OF1 and OF2 produced 34.9 and 23.5% more protein than CF (**Table 1**). Protein production for feed in the form of stover biomass had significant differences in both cycles ($P<0.05$). For Cycle 1, largest BP_{Feed} was obtained with the OF1 with a protein production 23.4 kg ha^{-1} higher than CF and 120.8 kg ha^{-1} higher than C. On Cycle 2, this treatment produced 42.9% more protein than CF (**Table 1**).

Table 1. Biomass production for food and feed in maize cultivated under different fertilisation treatments in Ahuazotepec, Mexico.

Fertilisation treatment	BP_{Food} Cycle 1 (kg ha^{-1})	BP_{Feed} Cycle 1 (kg ha^{-1})	BP_{Food} Cycle 2 (kg ha^{-1})	BP_{Feed} Cycle 2 (kg ha^{-1})
OF1	1076.4^{a}	550.2^{a}	945.9^{a}	483.5^{a}
OF2	1043.4^{a}	547.1^{a}	865.9^{a}	454.1^{ab}
CF	1091.4^{a}	526.8^{ab}	700.9^{ab}	338.3^{ab}
C	770.2^{b}	429.4^{b}	468.2^{b}	261.0^{b}

Letters indicate differences between treatments ($P<0.05$), means that not share a letter are significantly different (Tukey method, α=0.05).

Nutrient cycling efficiency

The application of the fertilisation treatments changed the yield of maize with respect to C. Organic fertilisers produced an average increase in yield of 4.2 Mg ha^{-1} (OF1, Cycle 1 IY=3.1, Cycle 2 IY=5.7 Mg ha^{-1}), while CF average IY was 0.9 Mg ha^{-1}. In second cycle OF1 and OF2 increase the IY value 2.3 Mg, on the other hand CF decreases the indicator value by 0.5 Mg.

Energy consumption in maize production

Energy consumed in maize production was similar in both cycles (**Table 2**). C had the minimal energy consumption (3459.8 MJ ha^{-1}), the maximum value was obtained with OF2 (21517.9 MJ ha^{-1}). In C and CF between 84.4 and 96.8% of the energy used is non-renewable, on the other hand, with *nejayote*-manure fertilisers between 79.6 and 80.4% of the energy is renewable (**Table 2**). Direct and indirect energy distribution is similar in organic and inorganic fertilisation (**Table 2**).

Table 2. Average energy consumption for maize production with organic *nejayote*-manure fertilisers in Ahuazotepec, Mexico.

Fertilisation	Direct Energy (MJ ha^{-1})	Indirect Energy (MJ ha^{-1})	Renewable Energy (MJ ha^{-1})	Non-Renewable Energy (MJ ha^{-1})
OF1	2801.1	17841.8	16434.7	4208.2
OF2	2801.1	18716.8	17309.7	4208.2
CF	1781.8	15369.7	546.3	16605.2
C	1775.1	1684.7	539.6	2920.2

OF1 = 75 m^3 ha^{-1} Nejayote + 50 t ha^{-1} ovine manure, OF2 = 150 m^3 ha-^{1} Nejayote + 50 t ha^{-1} ovine manure; CF= chemical fertilisation 120N - 60P – 30K; C= unfertilised treatment.

4. Discussion

Sustainability and circularity assessment

Soil Quality Index (SQI)

Obtained SQI to evaluate changes derived from agroecological fertilisation practices like *nejayote*-manure fertilisation, includes soil indicators such as organic matter and nutrients content, all these properties were reported in soil quality evaluations [19–22] because their contribution to improve soil sustainability and quality [7]. Manure addition increases soil quality at least 40% with respect to the chemical fertilisation [12]. This trend was observed in *nejayote*-manure fertilisers which had the high SQI, even with adverse climatic conditions climatic conditions. Conversely, CF had a negative trend in SQI, like values reported by [12,23]. An intensive conventional management leads soil to compaction, erosion, and degradation, although soil fertility improves in short term because the chemical fertiliser applied, in a long-term organic matter and nutrient content decreases affecting in a negative way soil quality [23].

Yield and biomass

Manure application increases SYI with respect to the CF [12,24] this trend was also reported with organic amendments such as biochar and vermicompost [25], it indicates productivity and sustainability improvements. Although some organic fertilisers evaluations did not find significant differences in grain yield due to the application of manure [6] or compost [26], an added benefit by combining organic and chemical fertilisation was reported. In this evaluation the SYI of the OF1 shows the highest value of the treatments, like single manure applications [27]. Organic amendments increase nutrient availability, organic matter content, and crop yield [25]. Use of organic manure contributes to a prolongated availability of nutrients due the slow-release action compared to the rapid solubility of chemical fertilizers [27].

In an agroecosystem, available nitrogen affects yield and protein content [28,29]. In this two-cycle experiment, biomass for food and feed was increased due the organic fertiliser applications, those results were consistent with an increase of 18 and 37% in crude protein reported due the biochar and vermicompost application [25]. Calcium content improves the amount of nitrogen used by the plant for biomass production; this could explain the higher protein content obtained with organic fertilisation, which coincides with those reported by [29] in corn grain fertilized with calcium nitrate and with [13] who report higher protein in flours obtained from corn organically fertilised.

Nutrient cycling efficiency

Recycling nutrients contained in waste from livestock or agroindustry contributes to closing nutrient cycle and reducing their pollution potential [8,9], improve soil properties [6] and could increase crop yield in a sustainable way. Organic fertilizers *nejayote*-manure increases agronomic efficiency compared with CF, this finds coincide to [15,30] and could be explained by the soil quality improvement, the enhanced efficiency in nutrient use, and mineralization processes [24,31], also in acidic soils, maize nutrient use and yield have a better response to the manure application [32]. Yield increase due to the *nejayote*-manure fertilizers application, was maintained even under adverse climatic conditions, this behaviour has been observed with other organic amendments [30].

Energy consumption in maize production

In conventional maize production systems, the greatest amount of energy used comes from non-renewable sources such as nitrogen fertilisers and fuel [18]. In CF urea represented 54.2% of the non-renewable energy consumed, this value coincides with [17]. Conversely, production systems where residues are used as organic fertilisers are less dependent on fossil fuels and non-renewable mineral resources [33] reducing the effect of price variations in production costs and the chemical fertiliser dependence [34,35]. Chemical fertilisers and fuel in maize production could increase emissions of carbon dioxide and greenhouse gases, contributing to global warming and its negative environmental implications [18,36]. Thus, transition to circular agro-food systems integrating crop, livestock, and agro-industrial production could reduce production costs and allow nutrients return to the field [8].

5. Conclusions

Agroecological practices such as organic fertilization leads to improvements in soil quality and crop productivity. According to the results, it is possible to say that the application of organic fertilisers *nejayote*-manure (OF1, OF2) improves soil quality, promoting stable yields as Sustainable Yield Index (SYI) obtained indicates. The recovery of nutrients contained in manure and *nejayote* can mitigate the pollution potential of livestock and agro-industrial maize processing. Recycling these residues as fertilisers for maize production contributes to closing the nutrient cycle, increasing the circularity of the agroecosystems and improving sustainability in maize production. Use of *nejayote*-manure fertilisers could be an option to address soil fertility problems and chemical fertilizer dependence in the maize agroecosystem in Mexico. Finally, since it also reduced the no-renewable energy consumed in maize production its adoption could help smallholders who have limited economic resources.

Supplementary Materials: Not applicable

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