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Effect of poultry wastewater irrigation on nitrogen, phosphorus and carbon contents in farmland soil

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Abstract: The goal of this study was to assess the suitability of poultry wastewater for the irrigation of farmland soil as a possible substitute for regular water and fertilizers. The vertical and spatial variability of soil total nitrogen (STN), soil total phosphorus (STP) and soil organic carbon (SOC) was analyzed during the growing season of summer maize in two types of soil: an experimental group (EG) soil, irrigated once only with poultry wastewater, and a control group (CG) soil, irrigated once only with regular water. Results revealed no difference in STP concentration, SOC concentration, nitrogen storage and phosphorus storage between EG and CG soils (all $p>0.05$); STN concentration in the 5–15 cm layer and carbon storage were higher in EG soil ($p<0.05$) while remaining within safety limits. Overall, single-time irrigation by poultry wastewater enhances nitrogen and carbon content of soil and does not pose a serious risk of pollution for ground water.

Keywords: Wastewater; irrigation; soil; maize; growth.

1 Introduction

Wastewater issued from livestock can be used (either treated or untreated) to irrigate fields in the place of regular water. This approach offers the advantage of saving water while reducing the use of fertilizers and the cost of wastewater treatment [1,2]. Wastewater irrigation is especially practiced in Northern China, where water shortage is a serious issue: Northern China hosts 45% of the total population and 65% of the total arable land with only 19% of water resources [3–6].

Livestock wastewater, although useful for irrigation, is potentially polluting as it is usually characterized by higher levels of suspended solid and ammonium nitrogen as well as lower concentrations of oxygen than regular wastewater (*e.g.*, domestic wastewater and industrial wastewater). These components may alter the biochemical properties of soil and hence its fertility.

Farmland soil serves as a temporary sink of nitrogen, phosphorus and organic carbon, which constitute a nutritional source for crops. The soil is also a sink for atmospheric carbon as well as an important component of the global carbon stock [7,8]. Soil total nitrogen (STN), soil total phosphorus (STP) and soil organic carbon (SOC) play a significant role in determining soil fertility and crop productivity [9,10]. The distribution of nitrogen, phosphorus and carbon in farmland soil is affected by a number of factors, both internal (*e.g.*, composition, topography, physical characteristics of soil) and external (e.g., fertilization, irrigation, straw and climate) [11,12]. Among these factors, the quality of irrigation water is the most crucial to determine the distribution of nutrients [13]. Therefore, the monitoring of STN, STP and SOC levels under wastewater irrigation provides a way to determine the impact of wastewater on soil [14–16].

Most studies have focused on the effect of livestock wastewater irrigation on soil quality and plant productivity [17–19], whereas fewer studies have evaluated the impact of poultry wastewater irrigation. This study analyzes the effect of poultry wastewater irrigation on the STN, STP and SOC levels in farmlands during the growing season of summer maize, to determine whether this type of irrigation is sustainable from an agricultural and environmental viewpoint. Poultry wastewater is expected to pose a lower risk of pollution for soil irrigation than livestock wastewater due to its lower nutritional content [20,21].

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2 Materials and methods

2.1 Experimental design

The study was carried out at the Mingren Science and Technology Demonstration Base for Poultry Waste Reuse and Disposal of Shandong Academy of Agricultural Science in Jinan, China (36°47′02″ N, 117°00′24″ E) from May to October 2015, during the growth period of summer maize. Mean annual precipitation was 669–685mm, with 70–80% of the precipitation concentrated in July and August every year. Mean annual evaporation was 587 mm. The mean annual temperature was 13.8–14.7°C, and the frostless period about 211 days under monsoonal climate [22]. The soil was the sandy loamy soil type. The main cropping pattern in the experimental area was the winter wheat – summer maize rotation. Shallow tillage with straw return was widely applied. Both poultry wastewater and regular water were used for irrigation. Poultry wastewater was issued from a commercial farm producing laying hens. No medicines were used at any stage of animal's life, except for Chinese herbal medicines which were used during the breeding period.

Two field groups were used for experiments: the control group (CG), irrigated with groundwater, and the experimental group (EG), irrigated with poultry wastewater. Before experiments, both groups were only irrigated by groundwater and rain. Each group included three lots (10 m × 3 m each). Waterproof geotextiles (1.2 m deep) were arranged between experimental lots. Both groups were irrigated once by groundwater and poultry wastewater during this study, respectively.

Each farmland was planted with 7.1×10^4 summer maize per hm^2. The amounts of nitrogen, phosphorus pentoxide and potassium oxide supplied by fertilizers were 200 kg/hm^2, 120 kg/hm^2 and 120 kg/hm^2. Fertilizers were applied before sowing. Experimental farmlands in CG and EG were irrigated only once with 80 mm groundwater or poultry wastewater, respectively, during the jointing stage of maize. Pure nitrogen fertilizer (60 kg/hm^2) was applied again during the heading stage. Each experiment was performed in triplicate.

2.2 Soil sampling and chemical analysis

In order to investigate the variation of nutrients in soil during the growing season of summer maize, soil samples were collected from CG and EG fields before sowing and fertilization (June 5) and at various stages of summer maize life cycle: the seeding stage (June 27), the jointing stage (July 25), the heading stage (August 26), the filling stage (September 16), and the mature stage (October 8). Five sampling sites were randomly selected in each plot. Soil samples were taken from four layers at various depth (0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm), placed in separate plastic bags, sent to laboratory, purified, air-dried, and passed through a 100-mesh sieve before analysis. The soil bulk density at each soil layer was measured with the ring sampler method. Soil moisture was calculated as the weight difference between wet and oven-dried soil. Soil pH was determined using a pH-meter with a soil-to-water ratio of 1:2.5. Soil total phosphorus (STP) concentration was measured by an ultraviolet-visible (UV–Vis) spectrophotometer (UV-8000S, METASH, China) after H_2SO_4+$HClO_4$ wet-digestion; the soil total nitrogen (STN) by the semimicro-Kjeldahl method; and the soil organic carbon (SOC) by potassium dichromate-external heating method [23]. Groundwater and poultry wastewater from broiler farms were used to irrigate two experimental farmlands. Chemical oxygen demand was evaluated by the potassium dichromate method; total nitrogen was measured by the test-in-tube alkaline persulfate digestion method. The persulfate digestion method and molybdate ammonium method were used for total phosphorus and phosphate phosphorus, respectively; Nessler's reagent colorimetric method and the cadmium reduction method were used for ammonia nitrogen and nitrate nitrogen, respectively. A Piccolo pH meter (Hanna Instruments) was used to measure the pH of water samples.

2.3 Statistical analysis

The SPSS 16.0 statistical package was used to calculate mean values and standard errors of STN, STP, and SOC. Analysis of variance (ANOVA) was performed with soil depth and irrigation water as the main fixed factors. Comparison of the STN, STP and SOC contents and storages in different surface soil layers was also performed with one-way ANOVA as well as C/N and C/P ratios. Origin 8.6 software was used to draw all figures.

3 Results

3.1 Soil nutrients

At any stage, EG soil showed higher STN concentration than CG soil (0.9–1.5 g N/kg soil *vs* 0.6–1.2 g N/kg soil). The highest STN value was reached at the mature stage in CG soil and at the heading stage in EG soil. For any

Table 1: Mean values of the main irrigation water parameters in each group farmland.

Parameter	pH	dissolved oxygen/ (mg·L⁻¹)	total nitrogen/ (mg·L⁻¹)	ammonia nitrogen/ (mg·L⁻¹)	nitrate nitrogen/ (mg·L⁻¹)	total phosphorus/ (mg·L⁻¹)	phosphate phosphorus/ (mg·L⁻¹)
Poultry wastewater	7.96	314.2± 10.7	416.3± 12.5	285.1± 7.8	123.9± 5.7	33.5± 2.7	25.7± 2.1
Groundwater	6.86	40.1± 3.2	6.0± 0.9	3.57±0.6	0.59±0.08	0.51± 0.09	0.33± 0.04

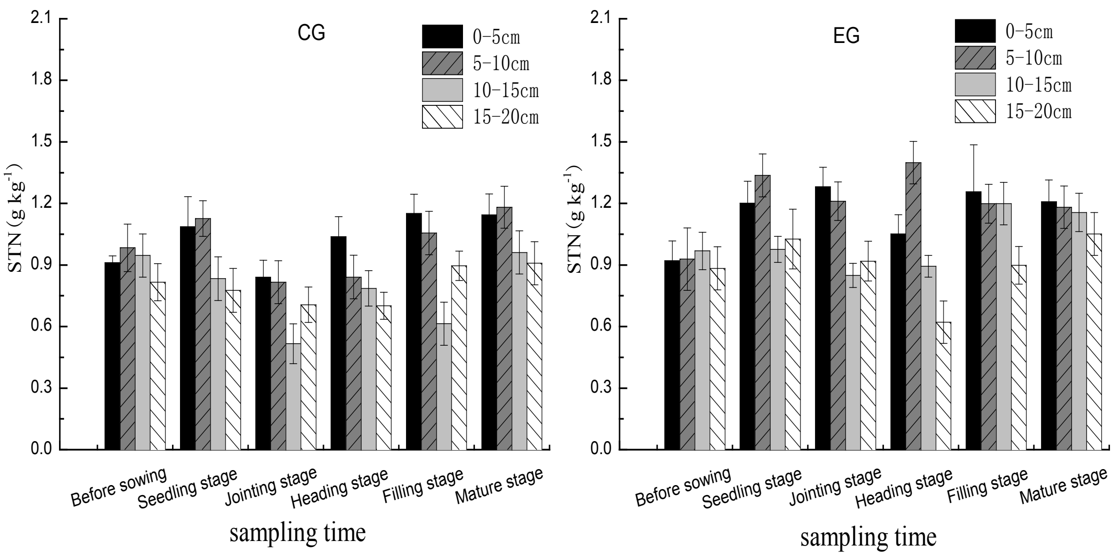

Figure 1: STN concentrations in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation.

given layer in both soils, STN values fluctuated over time. Surface layers (0–5 and 5–10 cm depth) showed higher STN levels than deep layers (10–15 and 15–20 cm depth) (Figure 1), although STN did not always decrease regularly with depth.

STP concentrations did not significantly differ between CG and EG soils (p>0.05), indicating that the total concentration of phosphorous in the soil (0.3–0.8 g·kg^{-1}) was not altered by poultry wastewater irrigation (Figure 2). In both soils STP reached the maximum values at the seedling stage. After seedling stage, STP steadily decreased, then increased again at the final (mature) stage. Like STN, STP was maximum on the surface layers (0–5 and 5–10 cm depth).

Similarly to STP, SOC concentration was not significantly affected by poultry wastewater irrigation (comparable SOC values between CG and EG soils; Figure 3).

Deep (10–15 and 15–20 cm) layers displayed significantly lower SOC than surface (0–5 cm and 5–10 cm) layers.

3.2 C/N and C/P ratios

As shown in Figure 4, no significant difference in C/N ratio was found between the experimental groups at any soil depth (p>0.05). In CG soil, the maximum C/N ratio was observed at the jointing stage in the 10–15 cm layer; in EG soil, the maximum C/N ratio was observed at the heading stage in the 15–20 cm layer. However, in both soils C/N ratio was lower than 14.2 and the overall trend was a slight decrease in C/N ratio during the growth of summer maize.

Conversely, the C/P ratio increased in both soils during the growth of summer maize (Figure 5). This observation may be explained by the fact that phosphorous was progressively absorbed by maize during the growth process. In both soils the C/P ratio remained essentially constant before the jointing stage, and increased to maximum (>20.0) after the jointing stage. In EG soil, the maximum C/P ratio was observed at the filling stage at all depths. In CG soil, the trend was less uniform as the maximum was observed at various stages depending on depth, and the ratio increased steadily until the mature stage at a 15–20 cm depth.

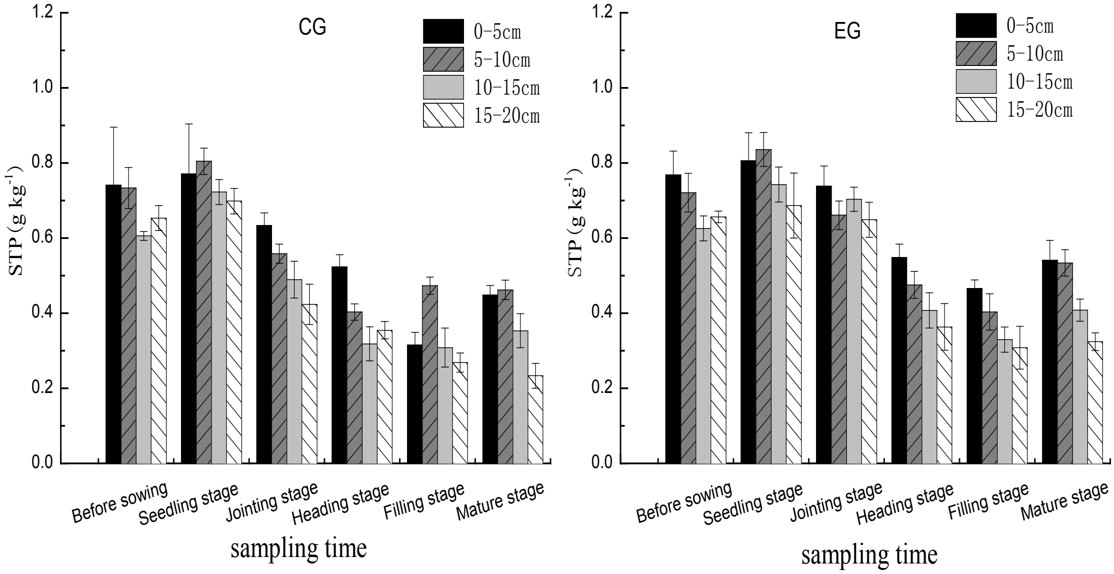

Figure 2: STP concentrations in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation.

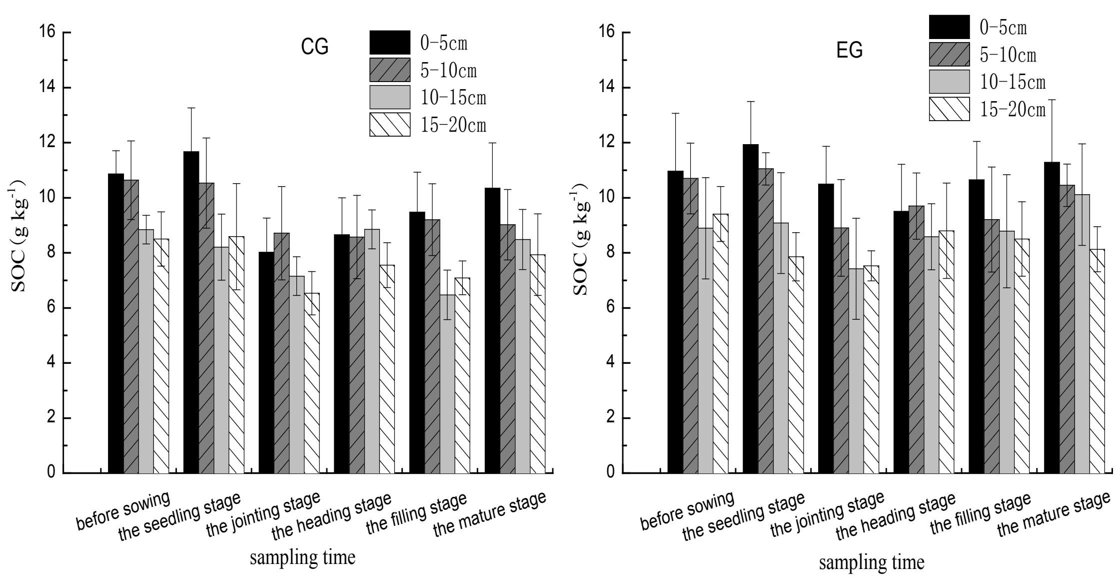

Figure 3: SOC concentrations in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation.

3.3 Nutrient storage

CG and EG soils had comparable bulk density (1.31–1.33 g cm^{-3} and 1.30–1.32 g cm^{-3}, respectively). Over the maize growth cycle, EG soil stored a larger amount of nitrogen than CG soil (N storage = 0.21–0.27 kg m^{-2} *vs* 0.24–0.30 kg m^{-2}; Figure 6). Phosphorus storage in CG soil increased first, then decreased; in EG soil, it followed the opposite trend. Nevertheless, there was no significant difference between the two soils in terms of P storage range (0.09–0.20 kg m^{-2}). Carbon (C) storage remained approximately constant with the growth of summer maize in both CG and EG soils. The two soils showed comparable change of C storage values, while C storage values in EG was greater than that in CG soil at any given stage (C storage = 2.02–2.55 kg m^{-2} *vs* 2.27–2.62 kg m^{-2} kg m^{-2}).

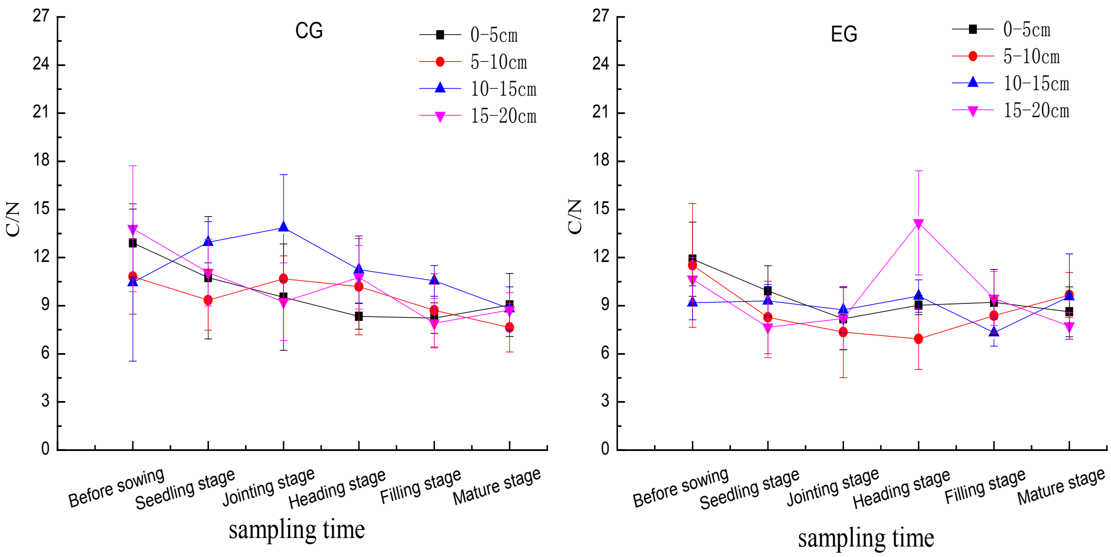

Figure 4: Temporal variation of C/N ratio in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation.

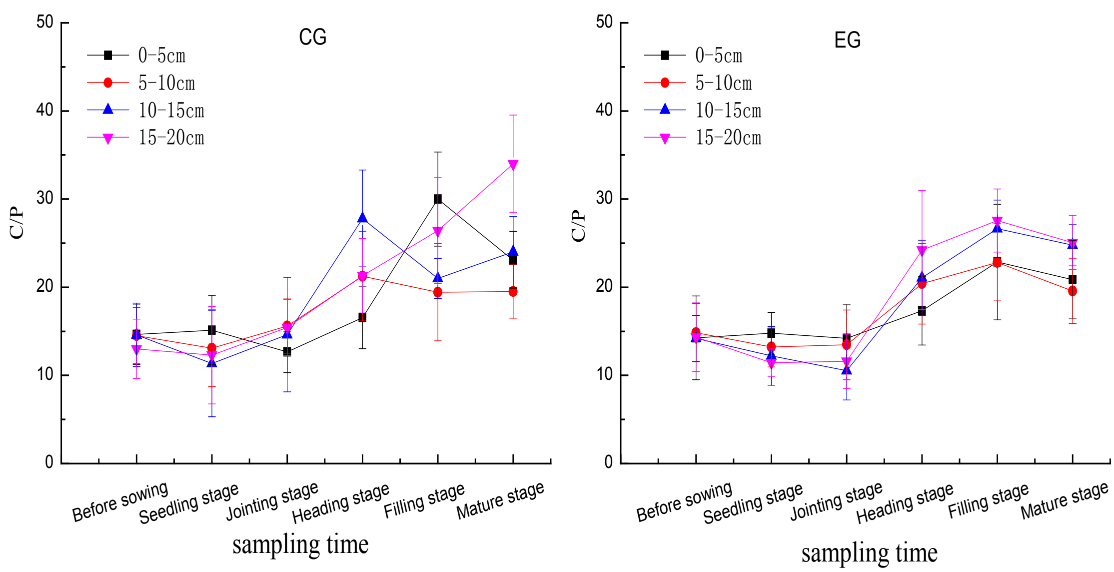

Figure 5: Temporal variation of C/P ratio in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation.

4 Discussion

The nutritional content in farmland soil is affected by many factors: not only irrigation but also rainfall and other agricultural practices (*e.g.*, tillage, straw return, and fertilization) [24–26]. The results are discussed in the light of the above factors.

4.1 Effect of poultry wastewater irrigation

Poultry wastewater used in the experiment contained higher concentrations of nitrogen (as ammonium, NH_4^+, and nitrate, NO_3^-), phosphorous (as orthophosphate, PO_4^{3-}) and organic matter than livestock wastewater (Table 1) [18,27].

Under both groundwater and poultry wastewater irrigation, the highest STN, STP and SOC concentrations were found on the outer soil layers (0–10 cm depth), and

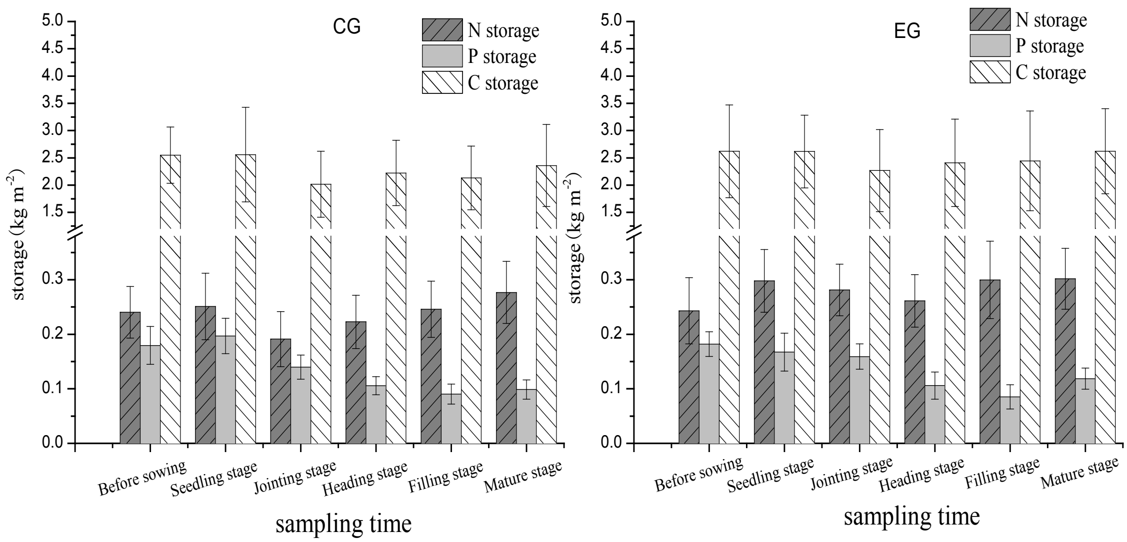

Figure 6: Temporal variation of N, P and C storage in the control group (CG) and the experimental group (EG) soils subject to poultry wastewater irrigation

decreased with soil depth, although not always with a regular trend. These results are in agreement with previous studies [28, 29].

In both soils STN levels remained approximately constant in time, presumably due to the balance of opposite effects: the supply of inorganic nitrogen by poultry wastewater and the action of nitrifying bacteria, which tend to increase STN; and the absorption of nitrogen by denitrifying bacteria and plants, which tend to decrease STN [30]. Although total nitrogen slightly accumulated on the 5–15 cm soil layer under wastewater irrigation, its concentration in the deep soil (15–20 cm layer) was lower than on surface, implying that single-time irrigation by poultry wastewater during the maize growing season poses no risk of groundwater pollution.

No significant difference in STP concentration was found between poultry wastewater irrigation and groundwater irrigation, despite the higher phosphorous concentration in wastewater. This result is in contrast with previous studies indicating that STP concentration increases significantly when applying irrigation by swine wastewater [31].

Measurements also indicate that irrigation by poultry wastewater, unlike that by livestock wastewater [32], does not cause phosphorous accumulation on soil surface. The observed difference may be due to the higher P level and longer application time of swine and livestock wastewater compared to poultry wastewater.

SOC levels were enhanced by poultry wastewater irrigation compared to groundwater irrigation. The increase in SOC under wastewater irrigation has been associated to a higher efficiency of nitrogen use [33], resulting into a crop yield increase of 50–150% [34].

The low (<14.2) C/N ratio indicates that the mineralization rate of organic nitrogen in soil is greater than the biological immobilization rate of soil mineral nitrogen [35–37], and therefore the concentration of inorganic nitrogen in soil is sufficient for maize. The decreasing trend in C/N ratio, *i.e.*, an increase in carbon content with respect to nitrogen in time, suggests an increase in the decomposition rate of organic matter during maize growth.

The high (>20.0) C/P ratios observed in both soils after the heading stage may be due to a higher absorption rate of phosphorous by plants in the late growth stages, or to the competition of soil microbes with soil for inorganic phosphorus, or both [38].

4.2 Effect of rainfall

Although both groups were only irrigated once during the growth season of summer maize (with poultry wastewater and groundwater, respectively), rainy season occurred between July and September, leading to the phenomenon of soil drying and rewetting. This process affects the physical, chemical, and biological properties of soil in several ways: 1) it modifies soil aggregation, porosity, and moisture [39–42]; 2) it reinforces the mineralization of nitrogen, phosphorous and carbon [43]; 3) it usually increases nitrogen absorption, although the amount of nitrogen absorbed by maize under sewage irrigation is lower than that under freshwater irrigation [44]; and 4) it favors the transformation of microbe macro-aggregates into stable micro-aggregates rather than primary particles [45,46].

4.3 Effect of agricultural practices

Agricultural practices such as tillage, straw return, and fertilization are often used to improve soil quality to grow crops. These factors, like irrigation, are responsible for the alteration of nitrogen, phosphorous, and organic carbon in the soil [47–50].

Tillage has positive and negative effects on soil. On one side, it aerates the soil, favoring the decomposition of organic matter and the activity of aerobic microorganisms; it dries the soil, facilitating planting the crop; it helps mix humus into the soil; and mechanically destroys weeds. On the other side, tillage decreases soil ability to store water, and causes the runoff of nutrients to deep soil layers, leaving the surface soil devoid of such components and causing eutrophication [51].

To counteract the loss of nutrients, tillage is often combined with straw return [52]. Straw is able to absorb and retain both organic and inorganic components with a double benefit: an increase in nutrient levels on the top layer of soil and a decrease in polluting substances runoff like fertilizers, which would otherwise end up in groundwater [53]. Previous studies have indicated that shallow tillage, in combination with straw return, leads to higher levels of STN, STP and SOC in the soil than conventional tillage without straw return [50,54]. In addition to increasing soil fertility, straw return can increase soil porosity, reduce soil bulk density, adjust the earth temperature, enhance soil water preservation, improve the activity of soil microbes and enzyme and enhance the efficacy of fertilizers [55–58], especially on the long term [59]. This nutrient-enhancing effect of straw return has also been observed in dry lands allocated to summer maize [60].

Fertilization is a simple and rapid method to increase the nutrients content in farmland soil on the short term [61]; however, it may cause soil acidification and decrease soil productivity on the long term [62]. Nitrogen fertilization supplies inorganic nitrogen, which is readily incorporated by plants. Part of inorganic nitrogen is also converted into nitrogen gas by denitrifying bacteria and returned to atmosphere, thus becoming unavailable to plants [63,64]. Phosphorous fertilization is mostly beneficial after the seeding stage, when phosphorous absorption by plants is the maximum [65]. On the long-term, the maximum P adsorption capacity of soil decreases, whereas the degree of P sorption by plants increases [54]. Organic fertilizers are a source of both organic nitrogen and carbon. Organic nitrogen is converted into inorganic nitrogen (nitrites and nitrates) by nitrifying bacteria [67,68]. Organic fertilization, although useful, can result into reduced soil porosity, reduced air and water permeability, soil hardening and eventually poor soil quality [69–72].

5 Conclusions

In conclusion, single-time poultry wastewater irrigation during the growth season of maize has the following effects on soil:

1. It increases the nitrogen concentration both on surface and in depth without affecting nitrogen storage; however, N levels remain within safety limits;
2. It has no effect on the concentration and storage of phosphorous;
3. It favors the decomposition of organic matter, increasing soil C storage.

Overall, single application of poultry wastewater in soil irrigation poses no pollution risk for groundwater.

Further studies with multiple-time applications are necessary to evaluate the long-term effect of poultry wastewater irrigation on soil quality and agricultural productivity, and eventually determine whether poultry wastewater can be safely used for irrigation on a regular basis.

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