Effects of Organic Amendments on *Solanum tuberosum* L.

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Contributor: María Antonieta Escobedo-Monge, Santiago Aparicio, Marlene Fabiola Escobedo-Monge, José Manuel Marugán-Miguelsanz

The potato (*Solanum tuberosum* L.) is the third most important food crop worldwide, after rice and wheat. The potato is one of the crops that produce more food per unit of time, water and area, even in more adverse climates in comparison with any other crop. It is also characterized by its extraordinary ability to adapt to different soil and climate conditions, occupying a leading role in the global food chain, and thus being considered by the United Nations Food and Agriculture Organization (FAO) as a food security crop. Likewise, the increase in world population leads to uncertainties in the food supply chain and it shows the need for high-yield crops.

Keywords: organic amendments ; composting ; heavy metals

1. Introduction

The integrated use of natural resources in the context of sustainable development should be considered, and for that purpose soil management will have a pivotal role in the improvement of agri-food production without compromising soil(s) fertility [1][2]. Agronomical practices have been directed in the last decades to the exploitation of existing resources in order to obtain maximum productivity, with relevant environmental consequences because of the applications of large amounts of agrochemicals and pesticides, decreasing soil biodiversity and fertility [3]. The agricultural use of residues, from cattle of urban origin, in the form of compost could be considered as an alternative that allows the minimization of waste generation by human activities and improves soil(s) fertility.

Nevertheless, the application of organic amendments may have additional potential risks on the environment, derived from its effects on the trophic chains, which are linked to their possible toxicity and persistence in ecosystems. One of the most relevant problems of the applications of compost for agronomical purposes stands on the possible accumulation of heavy metals in the plant tissues by absorption, thus leading to the possibility of being bioavailable to humans and animals through its consumption. The chemical forms in which they are found in the organic amendments and their evolution over time once incorporated into the soil will be determinant for metals in plant for the mobility of these pollutants and their degree of assimilation by the crops.

The potato (*Solanum tuberosum* L.) is the third most important food crop worldwide, after rice and wheat [4]. The potato is one of the crops that produce more food per unit of time, water and area, even in more adverse climates in comparison with any other crop. It is also characterized by its extraordinary ability to adapt to different soil and climate conditions, occupying a leading role in the global food chain, and thus being considered by the United Nations Food and Agriculture Organization (FAO) as a food security crop. Likewise, the increase in world population leads to uncertainties in the food supply chain [2][5] and it shows the need for high-yield crops [1][6]. For this purpose, the potato should be marked as one of the crops with greater genetic diversity, with the Germplasm Bank of the International Centre of the Potato (IPC) in Lima (Peru) including more than 7000 accessions of native, wild and improved potato varieties. Therefore, the need for developing new potato varieties with greater nutritional value and durable resistance to diseases is of global importance.

According to the FAO, it is estimated that around 792.5 million people across the world are malnourished, out of which 780 million people live in developing countries [7]. In transitional countries, stunting (shortness for age) and micronutrient deficiencies (iron, vitamin A, and zinc) in children coexist with obesity and nutrition-related chronic diseases (NRCDs), demonstrating the double burden of nutritional disease [8]. The various strands of malnutrition—undernutrition, hidden hunger and overweight—are interwoven in many ways, and there is a triple burden of malnutrition in growing numbers of countries and communities [9]. Biofortification of potatoes would not only increase the nutrient content in the potato, but also their bioavailability, offering a long-term sustainable solution to provide micronutrient-rich crops to people at nutritional risk.

2. Factors Involved in Increasing Potato Yield

Three main factors should be considered for the yield in potato production, the considered potato varieties, the physicochemical characteristics of the composts, and the edaphological characteristics of the soil. The use of wild and cultivated species as a source of resistance to biotic and abiotic stress is essential. Efficient wild species in the absorption of nutrients from *Solanum tuberosum* subspecies *andigenum*, resistant to the fungus *Phytophthora infestans* and viruses (potato virus A, potato virus X, potato virus Y) with European varieties or lines of *Solanum tuberosum* subspecies *tuberosum* with resistant genes to other types of viruses (potato leaf roll virus) were crossbreed. New clones were created and tested in 1991 in three phases [10], considering the resistance to the relevant viruses, tolerance to root-knot nematode and adaptability to arid and warm climates.

The chemical and physicochemical composition of the MSWC varies greatly according to the composting plant and seasonal variations. The humidity of organic amendments was less than 34%, with 40% being the maximum admissible value according to the fertilizer regulations in force in Spain. Furthermore, the CMC was moderately alkaline (pH 7.9–8.4), SMC was slightly alkaline (pH 7.1–7.8) compared to MSWC and ChMC, which are closer to neutrality. It must be emphasized that the compost had a process of washing with salts during the time of processing and storage, therefore the electrical conductivity in the MSWC was slightly saline with a range between 2 to 3 dSm^{-1}, being slightly higher in the others compost.

Despite the washes carried out, the contents in N and P in the MSWC and ChMC are higher than in the CMC and SMC, and the content in K was higher in the CMC than in the MSWC, ChMC and SMC. This may be due to the rich diet based on proteins and phospholipids of the human population. The P is a mineral that is added to many processed foods to enhance flavor, prevent discoloration, and preserve them [11].

The Carbon/Nitrogen (C/N) ratio of the materials applied as an amendment is considered as the simplest information on the mineralization capacity of organic material, since the contents of carbon and nitrogen are essential for the life and reproduction of microorganisms [12]. The C/N ratio of the different treatments at the time of their incorporation into the soil was very good with an average range of less than 10, this would indicate a very good transformation of the material with greater stability and with a good reserve of nutrients, which would allow it to be better assimilated by plants, not representing a limitation in the bioavailability of N for crops [13]. The Ca content was relatively higher in MSWC, in comparison with the other composts. The Mg and Na contents were usually lower than Ca and were slightly higher in the MSWC and the ChMC.

3. Effect of the Treatments on the Yield and the Mineral Content in the Tubers

3.1. Yield

Two stages were observed especially for the MSWC in all the varieties, and mainly clone A7677. The first stage takes place from 1998 to 2007 and is characterized especially by a sustained increase in the yield of potato production and mineral content, with a maximum observed between 2004 and 2007. While in the second stage (2007 to 2016) the yield of potato production and mineral content due to the MSWC decreases to values below the control. Regarding the application of MSWC, although the increase in performance in the first stage shows the effectiveness of the treatment, the sustained decrease in the second phase could be due to the interaction of micronutrients and heavy metals, which could affect the food security chain. In this second stage, the highest yield and mineral content was produced mainly by the ChMC, CMC and SMC. In general, the MF presented a low yield in the potato production and in the mineral content compared to the MSWC, except in the P content exceeding ChMC in some years. The latter was the second treatment to achieve the best yields. The consecutive applications of these organic amendments have produced a remarkable increase in the content of nutrients in the tubers with respect to the control, indicating increasing availability of nutrients for crops over time. However, the content of heavy metals is worrisome since their absorption and storage in the tissues of plants can be included in the trophic chain of living beings.

3.2. Macronutrients

A significant increase in the content of N (43 g kg^{-1}DW), P (9 g kg^{-1}DW) and K (48 g kg^{-1}DW) in the tubers with respect to the controls is inferred. The potato crop is particularly demanding in N, P and K, its quality will depend largely on the variety and the availability of nutrients.

1. Nitrogen.

Between 1998 and 2007, the MSWC has provided the highest N content in the tubers of the varieties Agria, Monalisa and Jaerla, only exceeded by clone A7677 (43 g kg^{-1}DW). In the 1998 to 2016 period, the ChMC is the second treatment to provide a high concentration of N, remaining constant along with the experiments. The highest concentration of N obtained in clone A7677 by the application of MSWC from 2004 to 2007 (43 g kg^{-1}DW) largely exceeds those reported by Cabalceta et al., (2005) [14], Alvarado et al., (2009) [15], Correndo and Garcia (2012) [16], Mahamudet al (2016) [17] and Fernandes et al., 2017 (16.4–22.7 g kg^{-1}DW) [18]. The yield obtained in all the varieties under this treatment (MSWC) may be due to the improvement in the availability of this element in the soil, as a consequence of the amount of nitrogen compounds added to it and the continued mineralization of N, favoring its absorption, higher plant biomass and as a consequence higher storage of this nutrient in its tubers [19].

2. Phosphorus.

The MSWC provides the highest P content in the tubers for the 1998 to 2004 period in the varieties Agria and Monalisa and for 1998 to 2007 in the variety Jaerla and in clone A7677. For 2007 to 2016, MF and ChMC lead to the highest P contents in the tubers. These P contents exceed those reported in the literature by Cabalceta et al., 2005 [14] and Alvarado et al., 2009 [15], and Mahamud et al., 2016 (1.2 to 4.7 g kg^{-1}DW) [17]. The addition of the considered amendments causes decomposition processes carried out by microorganisms, which would produce certain quantities and types of organic acids, siderophores, hydroxyl ions and other compounds [20], which would facilitate the gradual conversion of phosphates and weak retention of these in the solid phase of the soil. Therefore, the increase in the P content due to the compost favored an adequate development of roots, increase in the aerial biomass, improvement in the quantity and quality of the tubers in all the varieties, which resulted in better use of this nutrient by crops, especially under the treatment with the MSWC and ChMC (2004 and 2007).

3. Potassium.

For the 1998 to 2007 period, there was an increase in the K content with MSWC for the Agria, Monalisa and Jaerla varieties, only surpassed by the clone A7677 (48 g kg^{-1}DW). This K concentration exceeds those reported by Alvarado et al., 2009, Mahamud et al., 2016 [17], Jahanzad et al., 2017 [1] and Fernandes et al., 2017 (25.2–29.8 g kg^{-1}DW) [18]. Potassium is essential for the synthesis of starch and simple sugars and for the translocation of carbohydrates, thus playing a pivotal role in maintaining the vigor and efficiency of the potato plant. Along with N, P is the most necessary mineral for the growth of plants [21]. Furthermore, low K intake is associated with various non-communicable diseases, such as hypertension, cardiovascular diseases, chronic nephrolithiasis, osteopenia, etc. [22].

3.3. Micronutrients and Heavy Metals

The studied long-term treatments (1998 to 2016) show highly significant increases in micronutrient content with respect to the controls by consecutive applications of the studied composts (MSWC, ChMC, SMC, CMC and MF) when considering Fe, Mn, Zn, Cu. Additionally, relevant variations on heavy metal content (Pb, Cr and Ni) were inferred.

- Iron

Iron deficiency represents one of the most serious problems in micronutrient nutrition in humans worldwide [23] and there is a need to increase the amount of bioavailable iron in crops such as potatoes. Values of 15 to 20 mg kg^{-1}DW are considered as a baseline for Fe in potatoes [24]. In this long-term study, for the 1998 to 2007 period, the MSWC provides the highest Fe content in the tubers of the varieties Jaerla, Monalisa and Agria, only exceeded by the clone A7677 (118 mg kg^{-1}DW). The normal potato content of Fe is in the 50–250 mg kg^{-1} DW range [25][26], being largely dependent on the considered variety.

2. Manganese

This element was the only one that shows an increasing trend during all the experiments, for all the treatments and varieties Agria, Jaerla and clone A7677. In the 1998 to 2016 period, MSWC provided the highest Mn content for the varieties Jaerla, Monalisa, Agria and clone A7677 (27 mg kg^{-1}DW). ChMC was the second treatment to achieve a higher Mn content in Jaerla, Agria, Monalisa and clone A7677 (19 mg kg^{-1}DW). These values are within the normal range (20–300 mg kg^{-1}DW) and well below the phytotoxicity limits of 500 mg kg^{-1}DW [27]. Likewise, Mn contents reported exceed those by Baranowska [28], Ali and Al-Qahtani [29] and Fernandes et al. (2017, 6.7–11.5 mg kg^{-1}DW) [18]. Mn is another essential nutrient required in very small amounts in the human body [30]. However, the diet of the population based on cereals such as rice, wheat, cassava and corn contain insufficient amounts of this micronutrient [31]. Increasing the Mn content in tubers (biofortification) can help improve this insufficient intake.

3. Zinc

Another important micronutrient is this essential element because Zn deficit affects more than 30% of the world population [32]. Hence the relevance of crops that can supply Zn in greater quantities [33] such as potatoes, which contributes 2.6% and 3.2% of the daily human dietary requirements of Fe and Zn, respectively [34]. Likewise, Zn regulates the formation of ribosomes, auxins, cellular components and increases the resistance of the plant against drought and diseases [28], thus even mild deficiencies can have serious effects on the health and growth of plants. Even though the concentration of Fe and Zn in the potato is low compared to cereals and legumes, their bioavailability in potatoes may be higher due to the presence of high levels of ascorbic acid, which is a promoter of Fe absorption, and low levels of phytic acid (inhibitor) of the absorption of Fe [35][36].

4. Copper

A sustained increase in Cu content was observed in the 1998 to 2016 period for clone A7677 with MSWC (from 12 to 17 mg kg^{-1}DW), followed by CMC. For 1998 to 2007, MSWC treatment led to larger Cu contents for the varieties Agria, Monalisa and Jaerla. For the 2007 to 2016 period, the largest Cu content was inferred for CMC treatment with the varieties Agria, Monalisa and Jaerla. The available literature shows very different Cu content in crops depending on the type of soil and crop, although the normal range is 2–7 mg kg^{-1}DW for the minimum value and 20–30 mg kg^{-1}DW for the maximum value [27]. The highest concentration of Cu registered in studies was in 2007 with MSWC for variety Agria and clone A7677. These values are higher than those reported by Correndo and Garcia in 2012 [16], Brown et al., (2014) [37], Pozzatti et al., (2017, 5.4 mg kg^{-1}DW) [38], Alvarado et al. [15], Ali and Al-Qahtani [29], and Baranowska et al. (2017, 6.23–6.58 mg kg^{-1}DW) [28].

5. Lead

In the 1998 to 2016 period, MSWC provides the highest Pb content in the tubers of clone A7677 (6 mg kg^{-1}DW) and in the varieties Agria, Monalisa and Jaerla, observing a significant and sustained increase. However, in 2010 there was a reduction in the Pb content of 20% in the Agria variety and of 42% in the varieties Monalisa, Jaerla and clone A7677 with respect to 2007. Pb concentrations compared to controls increase with all treatments, leading to slightly larger values for SMC and ChMC than for CMC. The reported results are comparable to those obtained by Ali and Al-Qahtani (2012, 1.51 to 6.19 mg kg^{-1}DW) [29] in a heavy metal biomonitoring study and with those found in crops of potatoes exposed to irrigation by wastewater contaminated with Pb [26]. On the contrary, they were below those obtained by Tadesse et al., in 2015 [39], Jalali and Meyari in 2016 (19.5 mg kg^{-1}DW) [40] and Angelova et al. (50 to 54 mg kg^{-1}DW [41]. It should be remarked that Pb is not necessary for plants and can accumulate affecting different physiological and biochemical functions [42].

6. Chromium

There was a sustained increase in the Cr content for the 1998 to 2007 period for all the varieties, leading to the highest concentration with MSWC treatment for clone A7677 (20 mg kg^{-1}DW) and in the varieties Agria, Monalisa and Jaerla. For 2007 to 2016, CMC treatment led to the highest Cr contents in clone A7677 (16 mg kg^{-1}DW) and the varieties Monalisa, Agria and Jaerla. These values exceed the level considered as normal (0.03–14 mg kg^{-1}DW), going into the phytotoxicity range (15 to 30 mg kg^{-1}DW) [27]. Cr is an essential element for the normal metabolism of carbohydrates in animal and human nutrition [43] but for plants, there is no conclusive evidence of their essentiality in the metabolism [43][44]. Additionally, Stasinos et al., (2014) [45] point out that Cr falls into the category of heavy metal, which can be easily taken and bioaccumulated by tubers and food roots. However, it should be remarked that in 2004, the maximum content of Cr affect the yields obtained neither for clone A7677 (71 t ha^{-1}) nor for the varieties Agria, Monalisa and Jaerla. In 2007, there was only a decrease in the yields of the varieties Agria and Monalisa (40 t ha^{-1}) compared to the varieties Jaerla (54 t ha^{-1}) and the clone A7677 (76 t ha^{-1}), which showed a yield increase. These results agree with Paiva et al. [46], who proposed that Cr exposure in plants led to healthier conditions compared to control plants. Likewise, Guevara and Montes showed that increased exposure to Cr led to Cr concentration in the potato tubers [47]. Several studies show that there is a clear correlation between the content of this metal in soils and the stimulation of growth and the absorption of underground organs [45].

7. Nickel

MSWC provides the highest Ni content for the 1998 to 2007 period for clone A7677 (20 mg kg^{-1}DW) and in the varieties, Agria and Monalisa and Jaerla, decreasing and then remaining constant for the 2007 to 2016 period (4–9 mg kg^{-1}DW). In contrast, for 2010 to 2016, SMC, ChMC and CMC provide similar Ni contents in the varieties Agria, Monalisa and Jaerla and with the clone A7677. The highest Ni concentration exceeds normal values (0.02 to 5 mg kg^{-1}DW), going into phytotoxic levels (10–100 mg kg^{-1}DW) [27]. The reported results agree with those by Mahmood and Malik [48] but are larger than those by Khan et al., (6.84, 7.93 and 8.71mg kg^{-1}DW) [26] in potato crops exposed to irrigation by Ni-contaminated wastewater. Ni is considered an essential micronutrient for the growth and development of plants with several metabolic roles [49]. The maximum Ni contents (2007, into the phytotoxic range) were obtained for MSWC treatment in the clone A7677 and in the varieties Agria, Monalisa and Jaerla but they did not affect yields. However, in 2007, it is noted that only yields of the varieties Agria and Monalisa (40 t ha^{-1}) with contents of Ni in tubers of 13 mg kg^{-1}DW declined, compared with the variety Jaerla (54 t ha^{-1}) and the clone A7677 (76 t ha^{-1}) whose yields, on the contrary, increased, despite Ni content of 20 and 8 mg kg^{-1}DW, respectively. These results indicate that Ni has stimulated the growth and development of foliage, which agrees with the positive responses of plant growth in the presence of Ni [33] [50]. Nevertheless, the possible Ni toxicity should be considered, with a negative impact on photosynthesis, on membranes permeability, and on the decrease in the micronutrient's absorption [51].

4. Bioavailability of Micronutrients and Heavy Metals

A dynamic equilibrium between metal fractions determines the mobility and bioavailability (more than the total content of metals). The pH, the redox potential, and the quantity and types of Organic Matter (OM) and clays are the most important edaphic factors in their control [52]. The availability of Fe, Mn, Zn, and Cu would be scarce or very restricted in the crops because the considered soil is slightly alkaline (pH 7.4) and would explain the low Fe, Zn and Cu concentrations in the control samples. Nevertheless, the application of treatments, especially MSWC, leads to a considerable increase in Fe (56 to 118 mg kg^{-1}DW), Mn (9 to 27 mg kg^{-1}DW), Zn (28 to 34 mg kg^{-1}DW) and Cu (14 to 17 mg kg^{-1}DW). Therefore, adequate amounts of compost applied consecutively to the soils would act very favorably for Fe, Mn, Zn and Cu to be in the rhizosphere, and thus being usable by plants. In addition, soil pH also controls the processes of sorption/desorption and chemical speciation in the soils of Cr and other heavy metals such as Pb and Ni [42].

Consecutive addition of treatments to the soil, especially MSWC, increased Pb (3 to 6 mg kg^{-1}DW), Cr (15 to 20 mg kg^{-1}DW) and Ni (12 to 20 mg kg^{-1}DW) for all varieties, especially clone A7677. These results can be justified considering that the addition of organic matter could specifically affect the solubility and bioaccumulation of metals, generally causing variations in pH and ionic composition of the soil. Additional studies have also proposed that it may be also an indirect consequence of the microbiological activity [42].

Nonetheless, it should be emphasized that plants have an extraordinary capacity to absorb heavy metals depending on the species, shape, concentration and bioavailability of the metals in the soil, as well as on the composition of the OM and the microbiological activity [53]. The mechanism of accumulation of Pb, Cr and Ni still have not been elucidated for *S. tuberosum*, but involvement of membrane transporters involved in the absorption of Ca, Cd, Mn, Fe, Zn and Cu has been proposed [42].

The reported results show that the compost has increased the concentration of macro, micronutrients and heavy metals in the tubers of all the varieties, due to the greater availability of assimilable forms of these. The reported high Cr and Ni concentrations (in the range of phytotoxicity) do not lead to lower yields in potato production between 2004 and 2007, which is probably due to positive interactions between the absorption of minerals [33][43][50]. Moreover, results reported indicate that the concentrations of heavy metals (Cr, Pb and Ni) are not lethal for the plants, with no visible phytotoxic effects, especially during the first stage with the application of the MSWC (1998 to 2007).The lack of visual perception of phytotoxicity in the studied crops, with high contents of heavy metals (Cr and Ni) in their different organs, can provoke an increase in agri-environmental vulnerability with a potential risk in the food chain, due to the possibility of being bioavailable to humans and animals through their consumption [54].

The decrease in yield from 2007–2010, mainly with MSWC treatment, could be due to the cumulative effect not only of heavy metals but also of micronutrients. The use of organic amendments that involve an application of microelements above the requirements could generate an accumulation of both micronutrients and heavy metals that over time can be toxic to plants [55]. This could be from 2010, where a decrease in plant height, reduction in foliage growth, discoloration of leaves, necrosis, epinasty of young leaves was notorious, little or no flowering and smaller tuber size, which produced a lower yield in potato production (2010 to 2016) with the application of the MSWC compared to the other treatments. This reduction in the yields reached up to 83% in the variety Agria, 81% in the clone A7677, 80% in Jaerla and 78% in the variety Monalisa.

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