The hidden potential of digested sewage sludge: a recycling approach to combat desertification

Wastewater management and desertification are two of the main problems of the contemporary world. The purpose of this thesis is to suggest and validate possible solutions to combat these problems. Although they may appear to have very little in common, they can in fact solve each other's issues. Indeed, one cause of desertification is soil chemical degradation which is produced by five phenomena, which include a lack of nutrients and the deficiency of organic matter. In order to purify water nowadays, the increase in wastewater in the world means that it is necessary to develop water treatments which are more and more efficient. The byproduct of these treatments is sewage sludge (SS). SS represents the central core of this thesis because its high presence of nutrients and organic matter means it (or compounds extracted from it), could be a possible solution for soil chemical degradation and, hence, for desertification. Anaerobic digestion is one of the most common SS stabilization strategies because it simultaneously allows SS stabilization, energy recovery, and biomass waste reduction. For these reasons, anaerobically digested sewage sludge (SSAD) was chosen to perform all the experiments for this thesis. Firstly, four SSADs, derived from the same wastewater treatment plant but differently treated (primary, secondary, centrifuged and dried SSADs), were chemically characterized. A significant amount was found of nitrogen, phosphorus, organic matter and many meso- and micro-nutrients which are essential for plant growth. On the other hand, contaminants such as heavy metals were also found. The first two experiments evaluated whether the direct application of these digestates could have beneficial effects on plants and soils and therefore be considered a possible solution to fight desertification. Hence, at the beginning of the experiment, a desert-like soil was selected: alkaline, low in nutrients and in organic matter. Then, this soil was treated in six different ways: with the four SSADs, a mineral fertilizer and a control sample with sand. Finally, evaluation was made on whether beneficial effects on plants and soil occurred, or, whether, due to the presence of contaminants, there were phytotoxicity effects. Both experiments were performed in a controlled environment: firstly, in a climatic chamber and, secondly, in a greenhouse. From the results analysis it emerged that beneficial effects were found in plants with the use of SSADs when compared to plants grown on non-treated soil. For example, the biomass produced with the application of dried SSAD was up to 37.5 folds higher than the control samples. Moreover, in some cases, there were even better results with SSADs than with the mineral fertilizer; this was caused by the higher quantity of phosphorus, organic matter and microelements in SSADs. Generally, the dried and centrifuged SSADs gave better results than the liquid ones (primary and secondary) and the soil balance of nitrogen confirmed this result two months after the SSADs addition: in liquid SSADs, there was more loss of nitrogen, probably due to volatilization of NH_4^+. Positive effects were also found in the soil treated with SSADs, with an increment of nutrients and organic matter after two months from the treatments.

In order to complement this research, further investigation was made on the two specific compounds that gave SSADs better performances compared with mineral fertilizer: phosphorus and organic matter.

Nowadays, phosphorus reserves are being depleted while demand for P fertilizer is increasing. Furthermore, the phosphorus used in fertilizers is mainly derived from non-renewable resources (such as phosphate rocks) with high environmental costs of extraction. However, SSADs can be considered as an alternative and renewable source of phosphorus. Using a modern phosphorus fractionation method (SMT method), it was found that the majority of P contained in centrifuged and dried SSADs was inorganic. Additional fractionation of inorganic phosphorus showed that a higher proportion of inorganic P was non-apatite inorganic phosphorus (NAIP) rather than apatite phosphorus (AP). According to many authors, high values of NAIP fraction correspond to high percentages of bioavailable-P. In fact, it is well known that the quantity of total phosphorus (P-Tot) has little or no relationship with the P availability for plant nutrition and only a small proportion of P-Tot is bioavailable. One of the most used methods for bioavailable-P quantification in soils is the Olsen method which consists of a spectrophotometrical quantification after the phosphorus extraction with $NaHCO_3$. Hence, an experiment was carried out over a three-month period in which P fractions and $NaHCO_3$ extractable-P in soils were measured at different times. Three treatments were applied to the sandy alkaline soil: control (no treated soil), centrifuged (soil + centrifuged SSAD) and dried (soil + dried SSAD). From the results it emerged that, after the SSADs addition, there was a significant increment of $NaHCO_3$ extractable-P. Furthermore, during the 90 days of the experiment, the P-Tot remained constant in all cases and, the bioavailable-P (P extracted by $NaHCO_3$) decreased in control and centrifuged-treated soils. This decrease could be due principally to the precipitation of phosphorus with calcium: in fact, with the soil alkaline pH and with a high quantity of Ca^{2+} ions in soil solution, the formation of sequential calcium phosphates, less soluble over time, could be the principal process. Furthermore, it was even possible that P adsorption had occurred in a lesser quantity. These explications are in line with other literature studies. To describe the behavior of bioavailable-P ($NaHCO_3$- extractable P) on soils, four kinetic models were tested. The Elovich model seems to best describe the adsorptive-precipitate process of bioavailable-P in control and centrifuged-treated soils. None of the models tested described the behavior of bioavailable-P in dried SSAD tested soil, probably because, differently from the other treatments, there was an increment in P-bioavailability on the 14th day from treatment addition. The same behavior was also found in other works and the possible reasons for this increment may include the anoxic environment, the microorganisms or the presence of organic matter.
In addition to the direct land application of SSADs, there might be another strategy for fighting desertification: the extraction of specific compounds that can help combat the desertification process. For this reason, promising compounds contained in organic matter were studied: the humic acids (HAs). These natural polymers are also defined as “the black gold of agriculture” due to their beneficial effects on soil quality and plant growth. Extraction, quantification, characterization and encapsulation of HAs recovered from SSAD were performed. The protocol adopted for the extraction made it possible not only to obtain a HA extract with a HA concentration (26.87%) double that of the starting material (SSAD: 12.53%) but also to get rid of heavy metals. Electron microscopy and infrared spectroscopy provided insights into the peculiarities of the HA extract, revealing features on isolated HA comparable to those reported in the literature for what concerns morphology and chemical moieties. After that, the extracted HAs were encapsulated in alginate beads in order to have a slow release of HA in a soil solution. In fact, alginate molecules can form a physical hydrogel, which creates an ionic cross-linking between monomers of the alginate and two adjacent polymer chains of HA. Afterwards, HA-alginate beads were tested in a

greenhouse experiment with lettuce plants on poor sandy soil. An increment on the root apparatus of lettuce was revealed: +63% above the untreated control. In conclusion, the encouraging results of this last experiment suggest that HA extraction from SSAD is a promising strategy for the sustainable production of HA. Indeed, a slow-release bio-stimulant containing HA derived from waste was produced and positively tested, fulfilling the circular economy principles.

Future objectives could include the improvement of extraction yields of HAs, the implementation of the encapsulation technique and the investigation of other possible high-value compounds that can be extracted from SSADs. Finally, it is possible to affirm that both SSADs valorization strategies mentioned here are suitable for fighting desertification.