Intra-soil phosphogypsum recycling for environmental safety, higher soil sustainability and productivity

Valery Kalinitchenko\textsuperscript{1,2}, Alexey Glinushkin\textsuperscript{2}, Tatiana Minkina\textsuperscript{3}, Saglara Mandzhieva\textsuperscript{3}, Svetlana Sushkova\textsuperscript{3}, Ljudmila Il’ina\textsuperscript{4}, Dmitry Makarenkov\textsuperscript{5}, Tatiana Kovaleva\textsuperscript{2}, and Ilya Lobzenko\textsuperscript{3}

\textsuperscript{1}Institute of Fertility of Soils of South Russia, Persianovka, Russian Federation (kalinitch@mail.ru)
\textsuperscript{2}All-Russian Phytopathology Research Institute, Big Vyazemy, Russia (glinale1@mail.ru)
\textsuperscript{3}Southern Federal University, Rostov-on-Don, Russia (tminkina@mail.ru)
\textsuperscript{4}Southern Scientific Center of the Russian Academy of Sciences, Rostov-on-Don, Russia (Iljina@ssc-ras.ru)
\textsuperscript{5}Institute of Chemical Reagents and High Purity Chemical Substances of National Research Centre “Kurchatov Institute”, Moscow, Russia (makarenkovd@gmail.com)

Amelioration and remediation technology was developed comprises dispersed application and mixing of the phosphogypsum into the soil layer 20–45 cm with the intra-soil milling. The phosphogypsum doses 0, 10, 20, and 40 t ha\textsuperscript{−1} were studied in the model experiment focusing on the intra-soil passivation of Cd contained in phosphogypsum, environmental remediation, and amelioration of the Haplic Chernozem of South-European facies (Russia). The soil total and water-soluble Cd form content depend on geographical location, the ionic composition of soil solution, and soil genesis. The mean total Cd content in soils of South Russia is about 1 mg kg\textsuperscript{−1} SDW. The mobility of Cd in the soil solution, as well as its penetration into the plants, depends on the content of carbonates, pH, ionic composition of the soil solution. The mathematical chemical-thermodynamic model and program ION–3 developed for the quantitative characterization of Cd thermodynamic forms in soil solution. The forms of ion in soil solution were calculated accounting the soil solution calcium-carbonate equilibrium, ionic strength, and association of ion pairs \textsuperscript{CaCO}_{3}^0, \textsuperscript{CaSO}_{4}^0, \textsuperscript{MgCO}_{3}^0, \textsuperscript{MgSO}_{4}^0, \textsuperscript{CaHCO}_{3}^+, \textsuperscript{MgHCO}_{3}^+, \textsuperscript{NaCO}_{3}^−, \textsuperscript{NaSO}_{4}^−, \textsuperscript{CaOH}^+, \textsuperscript{MgOH}^+. The coefficient of microelement association \textit{k}_{as} was proposed for the calculation of the equilibrium concentration of microelement ion or heavy metal (HM) in soil solution. According to calculations, a Cd\textsuperscript{2+} ion mostly bounded to associates \textsuperscript{CdOH}^+, partly to associates \textsuperscript{CdCO}_{3}^0 and \textsuperscript{CdHCO}_{3}^−. The \textit{k}_{as} was 1.24 units in the control option and decreased to 0.95 units at a phosphogypsum dose 40 t ha\textsuperscript{−1}. The calculated ratio of “active [Cd\textsuperscript{2+}] to total Cd” reduced from 33.5% in control option to 28.0% in the option of a phosphogypsum dose 40 t ha\textsuperscript{−1}. According to calculation, the biogeochemical barrier for penetration of HMs from soil to plant roots was high after application of phosphogypsum. The standard soil environmental limitations for the content of Cd in soil overestimate the real toxicity of Cd. Re-evaluation of the current TENORM and other environmental limitations become possible. The new decision for intra-soil milling and simultaneous application of phosphogypsum was developed the chemical soil engineering technology to decide simultaneously the tasks of soil contamination decrease, soil amelioration and soil remediation. The technology based on the transcendental Biogeosystem Technique
(BGT*) methodology provides environmentally safe phosphogypsum application to soil. The BGT* management of ecosphere provides health and productivity. Indirect transcendental nature-similarity of technology provides the new niche of developing capabilities addressing environmental safety concerns of ecosphere management. The technology ensures geophysical, chemical, physicochemical structural and architectural prerequisites for the stable soil evolution, environmentally safe waste recycling, the healthy soil microbiome and phytopathogen suppression, high-quality soil biological production, and human health.

The research was financially supported by the RFBR, project no. 18-29-25071, and the Ministry of Science and Higher Education of Russia, project no. 0852-2020-0029.