SOIL SCIENCE ANNUAL
2020, 71(4), 281–299

https://doi.org/10.37501/soilsa/131615

Studies of technogenic soils in Poland: past, present, and future perspectives

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Received: 07.10.2020
Accepted: 11.12.2020
Associated editor: Ł. Mendyk

Keywords

Technosols
Urban soils
Mine soils
SUITMA

Abstract

For a long time, the soils covering areas strongly transformed by human were ignored in scientific discourse. Also, practice did not care much about these soils because of their unproductivity. Only the large post-mining areas reclaimed and transformed into a forest or agricultural land were more interesting both for science and practice. In the case of post-mining areas the term "soilless land" was used for a long time, especially in relation to areas which were not reclaimed. In this paper, the past studies (until the end of 20th century) of technogenic soils in Poland were described. Technogenic soils of urban and industrial areas appeared in scientific considerations in Poland in the second half of the 20th century. In those times, soil properties on disposal sites were mainly investigated as a basic information for further design of technical and biological reclamation on disposal sites. Two Polish scientists should be emphasised as the world pioneers in concepts and studies of technogenic soils: (1) Michał Strzemski, who proposed a classification scheme for soils in urban and industrial areas, as well as listed the tasks for future studies of these soils, and (2) Tadeusz Skawina, who focused on the dynamic and directions of the soil-forming processes on the mine spoils in the context of their reclamation. Moreover, studies of technogenic soils in the last two decades were also shown in the paper. From the beginning of the 21st century the scientific research gained momentum. Nowadays, Polish researchers have great achievements in studying technogenic soils, including investigation of their properties, genesis, evolution, classification, biological features etc. Furthermore, we drew some outlines for future studies of Technosols.

1. Introduction

Technogenic soils, i.e. soils created or significantly transformed by humans in the industrial and urbanised areas, are recently among the most intensively studied soil groups (Kabała and Greinert, 2020). The studies have been carried out in many countries, after both scientists and politician have considered that majority of human population already lives in the areas, where such soil predominate. Poland has experienced tremendous industrial growth and urbanisation after the second world war, which also, unfortunately, had an extensive negative impact on the soil cover, regarding both its naturalness and quality (Bielska et al., 2015). It is clear since a long time, that the sites, including their soils, degraded by mining, industry, waste storage, transportation etc. may create a risk for human health and for the other organisms, thus require special attention, monitoring and reclamation (Sutkowska and Teper, 2015; Karczewska and Kabała, 2017; Warchulski et al., 2019; Józefowska et al., 2020).

The aim of the present paper is to show the achievements and contribution of Polish research to knowledge about the soils of urban, industrial, traffic, mining and military areas (SUITMA), regarding their properties, concept of their genesis and development. Most of these soils fulfil in majority the criteria for technogenic soils in a sense of Polish Soil Classification (Kabała et al., 2019) and many fulfil criteria for Technosols, as defined by WRB classification (IUSS Working Group WRB, 2015). Historical studies (till the end of 20th century) are presented, as well as the main contemporary (last 20 years) study directions are described. Moreover, general future perspectives for Technosol studies are outlined.

2. History of studies of technogenic soils in Poland

Research involving the human-affected soils in Poland has its long history, as it started in mid-1950s. It has to be emphasised that the terms "technogenic soils" and "Technosols" were not used in that times. More frequently used terms were for example "mine/urban soils" or "soils of mine/urban areas". Studies of technogenic soils from the very beginning acted multidirectional. In addition to analysing of soil properties, some effort was focused on the spatial diversity, classification and cartography, possibilities of urban land use and reclamation and remediation. Experts in soil science and reclamation of degraded sites dealt with these topics in parallel.

2.1. Soils in urban areas

The first elements of urban soil description appeared in the 1950s. In that time, a new field of science – urban physiography – was developed and the necessity of detailed urban environment description, including soils, was noted (Dziewoński, 1955). In a request, Strzemski (1955) proposed an original concept of soil classification in urban areas, based on his extensive observations rather than detailed studies. Strzemski (1955) highlighted the necessity of pedological investigations and indicated a number of detailed tasks for future urban soil studies, that covered:

1) the initial phases of the soil-forming process from the natural and artificial materials,
2) biological activation of soils by bacterial inoculation,
3) activation of „artificial" soil formation of sandy/skeletal soils by adding the natural clay minerals (bentonites),
4) the use the synthetic substances to accelerate the structure formation in urban soils,
5) the weathering processes on slag and mine heaps,
6) fertilization and chemical transformation of soils in urban and mining areas,
7) physical and water properties of various kinds of excavated materials as possible soil substrates,
8) agrotechnical methods for soils devastated or transformed by man,
9) phyto-melioration of soils developed from anthropogenic substrates.

Strzemski's (1955) concepts were completely new and not immediately found a positive response, in particular in case of urban soils.

Detailed studies of urban soils in Poland have commenced since early 1970s. They were mainly focused on chemical properties of soils of urban green areas, especially the roadside greenery, in Warsaw (Dobrzański et al., 1971; Czarnowska, 1975, 1978; Czerwiński, 1978) and Wrocław (Roszyk and Roszykowa, 1975). The studies concerned in particular the soil salinization (due to the use of salts for de-icing of roads and pavements) and contamination with trace elements, in particular with lead. Some research was conducted also in the big urban parks, like Łazienkowski Park (Dobrzański et al., 1975a, 1975b) and Saski Park in Warsaw (Dobrzański et al., 1977). Based on these studies, a new extensive proposal of urban soil classification was derived (Konecka-Betley et al., 1984).

Parallel to pedologists, studies on anthropogenic materials in urbanised areas were carried out by researchers from other disciplines, e.g. civil engineering. Racinowski (1976) divided the dumped soils into construction embankments and uncontrolled embankments. The first ones resulted from controlled activity, i.e. planned construction of earthworks and soil strengthening. A term 'uncontrolled embankments' described various types of landfills.

The investigations during next two decades have focused mainly on soil contamination, including the content of trace elements in plants and animals. The studies, carried out in various green areas of Warsaw, showed that human activity has destroyed the natural arrangement of soil profiles, which is evidenced by: (a) the change of morphology of soil profiles, (b) the emergence of calcium carbonates (e.g. from cement), (c) change of soil reaction from acidic to alkaline, (d) accumulation of organic substance in the upper layers of anthropogenic soils, and (e) accumulation of trace elements; the latter two phenomena – mostly in the topsoil layers (Czarnowska and Konecka-Betley, 1977; Czarnowska, 1980; Czarnowska et al., 1983, 1995, 1996, 1999). The highest accumulation was reported for Cd, Zn, Pb and Cu, while much lower for Mo, Fe, Ni and Cr. The highest concentration of metals in the soils, plants and animals was detected in the surroundings of the streets and industrial plants. Czarnowska (1980) claimed that the accumulation of trace elements in the soils, mosses, tree leaves, grasses and animal tissues can be a measurable indicator of the antropization of urban soils and, in a broader sense, the antropization of the urban environment. Studies on chemical transformation of urban soils, including transformation of soil reaction, salinity and contamination with trace elements were carried out also in other Polish cities, including Łódź (Czarnowska and Walczak, 1988), Lublin (Filipek and Badora, 1992; Kukier 1985, 1991), Kraków (Komornicki, 1986), Bydgoszcz (Malczyk et al., 1996), Szczecin (Wojcieszczuk, 1981, 1982; Wybieralski and Maciejewska, 1999), and numerous small towns, including Oława (Roszyk and Strojek, 1983) and Tomaszów Mazowiecki (Kabała, 1995).

The research on the spatial variability of urban soils in Warsaw, continued by Czerwiński and Pracz (1990a, 1990b), has emphasised the great role of construction and demolition waste (CDW) in the further soil formation. The authors distinguished a number of soil types and subtypes, such as mechanically transformed soils (with mixed horizons, truncated topsoil, etc.), dumped soils (further divided according to the type of artefacts) and chemically transformed soils (saline soils, soils contaminated with heavy metals).

Extensive research on urban soils was initiated in Zielona Góra in 1990s (Greinert, 1998a, 1998b, 1998c, 1999a, 1999b, 2000a, 2000b, 2000c, 2000d, 2003), concerning the morphological transformation of soil profiles, changes of soil physical and physico-chemical properties, as well as soil pollution and respective remediation techniques. The latter aspects are particularly important during the dynamic grow of the cities or remodelling of their internal structure. During that process, many former industrial sites change their functions that requires a recognition of the risks, commonly related to soil contamination (Greinert, 2000b).

2.2. Soils in industrial and mining areas

The studies of technogenic soils in industrial and mining areas in Poland date back to 1950s. Skawina (1958a, 1958b) started his field research and experiments aiming in biological improvement of industrial waste lands (brownfields) in 1955. Skawina has illustrated the initial stages of soil formation on the waste heaps in the Upper Silesia region, where bituminous coal has been mined since centuries back. Various forms of soil deterioration resulting from atmospheric pollution (dust and smoke) and mining activity (Skawina, 1958a), as well as the succession of natural vegetation and the changes in physical properties and chemical composition of the parent rock in various phases of soil development (Skawina, 1958b) were discussed. The author noticed that soils on the dumps from coal mining are still on the initial developmental stage, even in case of the oldest dumps, covered with tree stands or used as agricultural lands. He found that the intensity of parent material transformation is the highest in the first stage of soil formation, then it becomes slower and less evident. Also, Skawina (1958b) paid attention to the strong spatial heterogeneity of soils on mine dumps. He noticed that differences in the direction and advancement of the soil-forming processes are mainly determined by the following factors: (1) type of material and age of the dump, (2) height, shape and severity of erosion, (3) weathering of rocks, (4) thermal activity of coal dumps due to burning of coal remains dispersed inside the dump, (5) microclimate, (6) water properties, (7) chemical properties, and (8) type of vegetation in adjacent areas. Skawina (1958b) stated that bringing surface layers of mine wastes to chemical equilibrium is the most important aim of the biological reclamation of dumps. This allows to skip over several dozen years of the natural soil development under the slow plant succession and, consequently, allows to reclaim the dumps within much shorter time of the years instead of decades. Skawina and his co-workers are pioneers of land reclamation in Poland, who gave the basis for preparation of plans/projects of restoration of areas destroyed by industrial and mining activity (e.g. Skawina, 1969; Skawina and Trafas, 1971; Bolewski and Skawina, 1972; Skawina et al., 1974; Eckes et al., 1986).

Strzyszcz (1978) conducted lysimetric (column) experiments, which imitated a natural weathering of wastes on the coal mining dumps and gave an insight into possible directions of weathering processes in young technogenic soils. He found that (1) the wastes from bituminous coal mines are very diverse in terms of their physical and chemical properties as well as mineral composition; (2) properties of soils on surfaces of dumps are controlled by the rate of weathering of soil substrate; (3) the salinity of substrate changes as the weathering proceeds; (4) pH changes very dynamically in the weathered wastes; (5) mineral fertilization (mainly with nitrogen) is necessary in the first years of reclamation to improve the plant growth and to allow plants to survive seasonal droughts and near-ground frosts; (6) phosphorus fertilization should be done three and four years after plant introduction. One of the most important issue which should be recognized before plant introduction is a susceptibility of mine spoils to acidification due to sulphide weathering (Strzyszcz, 1978); therefore, he developed a rapid laboratory method based on the oxidation of wastes by hydrogen peroxide (Strzyszcz, 1988).

The studies of soils on dumps of open-pit lignite mines and their reclamation were initiated by Skawina (1963) and then continued by other researchers (e.g. Bender, 1980, 1983; Gołębiowska and Bender, 1983; Gilewska, 1991; Bender and Gilewska, 2004; Bender, 1995; Krzaklewski and Mikłaszewski, 1996; Szafrański and Stachowski, 1997). One of the most important achievements gained in the “Konin” lignite mine (central Poland) was relatively rapid transformation of the dumped wastes into fertile agricultural soils. It must be, however, stated that the wastes from the open-pit lignite mining noticeably differed from the wastes of bituminous coal mining, as the former mainly consisted of the Pleistocene materials, like glacial till and glacio-fluvial sands (Znamirowska-Karaś, 2001).

The remediation methods developed in the Konin region, known as “reclamation model of the Polish Academy of Sciences”, although successfully applied in Konin, could not be universally applied due to high diversity of materials deposited on mine dumps. An adaptation of reclamation methods for phytotoxic acidic spoils from lignite open-pit mine was conducted by the group of Greinert (1988). The concept presumed strong stimulation of primary soil forming processes by agricultural engineering and high doses of NPK fertilization. The main problem to solve was an extremely low pH (about 3) caused by pyrite and marcasite weathering, which eliminated introduced plants and facilitated erosion on the uncovered slops. The use of multistage soil reclamation with the target afforestation with Scots pine effectively hampered the erosion (Greinert, 1995, 1996, 1997). The research showed that the elements of reclamation which are crucial to reach their expected effectiveness are as follows: (1) homogenization of soil properties by deep mechanical cultivation, (2) neutralization of soil acidity, (3) fertilization with large NPK doses (unusual for ordinary forest cultivation), 4) preventing the suppression of pine growth by herbaceous vegetation, especially grasses.

Numerous studies have been carried out on the disposal sites of thermal power station ash (fly ash and bottom ash). Majority of the works focused on the methods of their reclamation and the influence of the reclamation on properties of developing technogenic soils (Maciak, 1978; Maciak et al., 1974, 1976a, 1976b, 1976c, 1979; Wysocki, 1988; Gilewska, 2004, 2006). Pioneer research concerning the weathering and soil-forming processes in soils formed from ash was conducted in the 1970s by Maciak and his co-workers (Maciak et al., 1976c). They have shown that reclamation and long-term cultivation of grasses and legumes caused the following changes in the properties of the ash substrate: (1) change in the colour from light to dark grey, (2) accumulation of pedogenic soil organic matter in the topsoil layer, (3) increase in the rate of cellulose decomposition indicating an increasing microbiological activity, (4) decrease in alkalinity, and (5) increase in carbonate content. That study was one of the first attempts in the world to discuss the pedogenic aspects of ash transformation into a soil. In 1980s, the works aiming to determine the chemical composition and the content of selected radionuclides in soils and plants cultivated on a bituminous coal dump were conducted by Rosik-Dulewska and Dulewski (1988).

Strzyszcz (1980) performed a thorough analysis of initial technogenic soils developed on the tailings from Zn and Pb ore mining and processing in the Upper Silesia. Physical and chemical properties, salinity, contents of trace elements (Zn, Pb, Cd, Mn, Cu), and microbiological properties of soils were studied. The properties of technogenic soils on the disposal sites near Zn and Pb mines in Trzebinia (south Poland) were then examined by Trafas (1988, 1996). Similar studies, conducted on the tailing ponds receiving the fine-textured wastes from Cu ore processing in Legnica region (Bogda and Chodak, 1995) have confirmed, that the technogenic soils developing from the tailings have unfavourable physical properties, are highly saline, alkaline and are contaminated with trace metals, that all together hampers the plant succession and soil development. Kabata-Pendias (1977) reported similar conclusions based on a pot experiments using the tailings from Cu ore processing.

Adamczyk (1965) and Swałdek (1983) studied the soils developed on old dumps of the abandoned iron ore mines in north-western region of the Holy Cross Mts., south-central Poland. Properties of these technogenic soils were compared with natural soils occurring in the surrounding of mine dumps. The natural soils were sandy and strongly acidic as they were developed from carbonate-free sandy parent materials, while the anthropogenic soils were mesotrophic and eutrophic, because the mine wastes were rich in carbonates and clay. The emergence of technogenic parent materials led to the formation of mesophilous beech and fir forests while the natural soils surrounding dumps were covered with various acidophilus communities.

Historical metal ore mining was widespread in the Sudeten Mountains, south-western Poland, marked with numerous waste dumps, either intentionally reclaimed or left for natural succession. Pedological studies in the Złoty Stok, initiated in 1990s (Szerszeń et al., 1994) have shown locally extreme soil contamination with arsenic and other metals, connected with widespread presence of the mining and smelting wastes in soils and on the soil surface. Arsenic and other trace elements were also found at high concentrations in the soils on the dumps in the Kaczawskie Mountains, where they often influence the plant and ground-water quality (Karczewska, 1999).

The pedological studies were conducted in 1980s and 1990s in sites of the former sand/gravel exploitation located along the Bóbr river, western Poland. Soils in these sites are featured by strong compaction, especially in the subsoil horizons, very low air capacity, acidic reaction, low content of organic matter and nutrients, as well as low soil enzymatic activity (Drab, 1988). Reclamation of these soils was carried out with initial mechanical soil preparation (deep ploughing) and mineral fertilization with high NPK doses (Drab, 1998). Although a noticeable soil fertility improvement was observed, some physical soil properties remained defective, as evidenced by excessive soil compaction and imbalanced soil air-water relations (Greinert and Drab, 2000). The horizon with gleyic properties was noted at the depth of 40–60 cm below the surface (Drab, 2002, 2004).

In the 1980s, the first Polish researches on the enrichment of soils in industrial areas with ferromagnetic iron as an indicator of the deposition of industrial pollutants was conducted (Strzyszcz et al., 1988). The studies concerned the analysis of the ferromagnetic properties of technogenic and urban soils located in Upper Silesia (Strzyszcz, 1989a; Strzyszcz, 1989b; Strzyszcz et al., 1994).

3. Present studies of technogenic soils in Poland

The 21st century brought a dynamic increase in the research on technogenic soils in Poland. These soils have become the subject of interest of most Polish research groups dealing with soils science. Further development of knowledge about land reclamation, properties of different technogenic soils, as well as other soils degraded by human activity was expressed by numerous books or university script publications. In connection with the 7th SUITMA conference held in 2013 in Toruń, north Poland, a few books were published (Charzyński et al., 2013a, 2013b) which gathered together chapters presenting studies on soils in urban, industrial, traffic, mining and military areas.

3.1. Technogenic soils in urban areas

In addition to numerous new investigations focusing on detailed aspects, some attempts have been made to derive more generalized conclusions. As an effect, the papers comparing soil characteristics in selected cities have appeared (Greinert, 2002; Hulisz et al., 2018a). Soil research has significantly extended using modern analytical methods. This gave the opportunity to recognize the processes occurring in SUITMAs, and to improve their classification.

The main lines of research concerning soils in urban areas (including Technosols) can be described as follows:

- Soil chemistry, especially contamination with heavy metals and rare earths elements, their spatial distribution, solubility and mobility (Kozanecka et al., 2000; Pasieczna, 2003; Kabała and Wilk, 2004; Kwasowski and Markiewicz, 2007; Kabala et al., 2009, 2011; Kostecki et al., 2015; Kwasowski et al., 2016; Gąsiorek et al., 2017; Plak, 2018; Różański et al., 2018; Lewińska et al., 2019);
- Impact of salt use for road de-icing on the salinization of urban soil and conditions for plants (Brogowski et al., 2000; Czerniawska-Kusza et al., 2004; Kochanowska and Kusza, 2010; Łuczak et al., 2020);
- Impact of soil sealing on soil properties (Charzyński et al., 2011a, 2011c, 2017b, 2018b; Piotrowska-Długosz and Charzyński, 2015; Mendyk and Charzyński, 2016);

- Soil development on buildings and other constructions, including military fortifications (Charzyński et al., 2011b; Charzyński and Hulisz, 2013; Charzyński et al., 2015a; Markiewicz et al., 2018; Pardela et al., 2020);
- Soils of urban areas – urban agriculture, allotment gardens, parks and other green areas (Oleszczuk and Baran, 2005; Charzyński et al. 2018a; Beroigui et al., 2020);
- Importance of artefacts for soil properties and their further potential development, with particular emphasis on the construction and demolition wastes (Greinert, 2003; Greinert et al., 2013a; Greinert and Kostecki, 2019);
- Scale of anthropogenic soil transformation in the urban green areas (Licznar and Licznar, 2005; Licznar et al., 2007; Kabała et al., 2010; Dradrach and Bogacz, 2013; Musielok et al., 2018);
- Pedodiversity analysis in the urban, industrial and traffic areas; its contribution to urban soil mapping (Kabała and Chodak, 2002; Skiba et al., 2013; Greinert, 2015; Hulisz et al., 2018a; Pindral et al., 2020);
- Classification of anthropogenic soils (Polish Soil Classification, 2011, 2019; Charzyński et al., 2013c, 2017a; Kabała et al., 2018, 2019);
- Urban and industrial areas history as a factor of soil development (Greinert, 2003; Chudecka, 2009; Mazurek et al., 2016; Charzyński and Hulisz, 2017; Hulisz et al., 2018a, 2018b);
- Functions of soils in the urban environment (Greinert, 2017);
- Characterization of soil properties and geochemistry in the military areas (Jankowski and Sewerniak, 2013; Jankowski et al., 2013; Lewińska et al., 2017);
- Identification of urban soil contamination using magnetometric methods (Magiera and Strzyszcz, 2000; Wawer et al., 2015b, 2017; Łukasik et al., 2015; Łuczak and Kusza, 2019).

Polish researchers made a great contribution to recognise properties and functioning of Ekranic Technosols, i.e. the soils covered with impermeable and nearly-impermeable layers (pavement, asphalt, concrete, etc.) (Charzyński et al., 2011a, 2011c, 2017b, 2018b; Kostecki et al., 2020). The impact of the soil sealing on microbiological and physicochemical properties of Ekranic Technosols was investigated in Toruń (Piotrowska-Długosz and Charzyński, 2015). Moreover, soil sealing degree as a factor influencing urban soil contamination with polycyclic aromatic hydrocarbons (PAHs) was studied (Mendyk and Charzyński, 2016). It was found that totally sealed soils are better preserved from atmospheric pollutants, including PAHs. Charzyński et al. (2017b) used indicators, such as geoaccumulation index (Igeo), enrichment factor (EF) and pollution load index (PLI), to quantitatively determine the impact of soil sealing on the content of elements (Cd, Cr, Cu, Hg, Fe, Ni, Pb, Zn). It was found that the sealing has influenced the soil properties and Ekranic Technosols are less exposed to the accumulation of pollutants. Very important issue in the context of soil sealing are the water problems commonly noted in the cities (Kostecki et al., 2020).

A few soil studies were also made to examine morphological and chemical properties of soils located within cemeteries and mass murder camps (Charzyński et al. 2011c, 2015b; Majgier and Rahmonov, 2012; Majgier et al., 2014).

Along with the dynamic development of cities, the share of the traffic areas (roads, railways, airports) significantly increases. These specific areas, both in terms of construction and exploitation, have long aroused the interest of soil scientists. Currently, research is conducted on the composition and chemistry of soils in roadside areas (Kostecki et al., 2015). It was demonstrated that the road modernisation is typically connected with replacement of soil material, thus those soils are relatively young and not polluted (Kostecki et al., 2015). Pesticide residues in soils along railways were studied by Winiarek and Kruk (2017). The properties of soils in a Toruń airfield were investigated by Charzyński et al. (2013d).

The urban soils tend to be highly heterogeneous in terms of their properties and spatial distribution (Greinert, 2015). Therefore the spatial analysis of impact of the urban sprawl and other dynamic processes on soil resources in cities seems to be one of the most significant current line of research (Hulisz et al., 2018a). Maps of soil diversity can be valuable tools in a supporting the urban spatial planning (Kabała and Chodak, 2002; Skiba et al., 2013). Pindral et al. (2020) proposed the original method based on landscape metrics and GIS for measuring pedodiversity index (PI) which enables to identify the areas of the most strongly human-transformed soils and soil losses. Research is currently ongoing on field validation of this method and its application in spatial-temporal analysis of the soil cover. Another studies (Gąsiorek et al., 2017; Kowalska et al., 2016; Krupski et al., 2017) showed that urban soils can be an archive of urban area development and activities of citizens in the past. Kabala et al. (2018) have suggested unification of variable tests for phosphorus determination in anthropogenic soils and argued for Mehlich-3 procedure as the most universal for a wide selection of soils.

An important element of discussion on technogenic soils is quantity and quality of artefacts in these soils. Urban soils are largely enriched in construction and demolition wastes (CDW), rubbish, slag, ash, translocated rock fragments, sludge, and household wastes (Greinert, 2003; Greinert et al., 2013a; Hulisz et al., 2018a). It causes changes in the soil composition, its sorption capacity and water retention, and thus affects the circulation of water and elements in soil. CDW as a mixture of different materials often contains lime and other compounds that are chemically highly reactive; whereas, other CDW compounds, like construction sands and gravels, are considered chemically inert.

The effect of urbanization on soil properties and soil organic carbon accumulation in topsoil was examined (Oktaba et al., 2014, 2018). The contents of polycyclic aromatic hydrocarbons (PAHs) were determined in the humus horizons of soils of park gardens situated in city centres (Kraków, Lublin, Miasteczko Śląskie, Szczecin, Zabrze, and Zamość) and in their outskirts (Bielińska et al., 2011). It was found that, the PAH content was much higher in soils of parks situated in the city centres than in soils of parks situated in the outskirts.

The pollution sources and distribution of Pb, Cd, and Hg in Urbic Technosols in Wrocław were investigated by Gmochowska et al. (2019). The studies showed that Pb and Cd concentrations in technogenic soils were higher than in the non-technogenic soils. Furthermore, distribution of metallic elements in Urbic Technosols was more erratic relative to the more predictable one in not contaminated soils due to many sources of pollution. Other studies in Wrocław (Hołtra and Zamorska-Wojdyła, 2018) showed that soils are contaminated mostly by Zn, Cu, and Ni. These studies did not demonstrate any correlation between metal concentrations in soils and the distance from the city centre, but confirmed the importance of local pollution sources (Kabala et al., 2009). Similar findings were reported by Dradrach and Bogacz (2013).

Magnetometric studies have been used to identify pollutants in urban soils caused both by emissions from municipal sources (low emission, traffic pollution, etc.) and as a result of the negative impact of industrial plants (Strzyszcz and Rachwał, 2010; Szuszkiewicz et al., 2018). Research on the impact of traffic pollution on the quality of roadside soils was conducted in several cities in Europe and Asia (Wawer et al., 2015a; 2015b; Łuczak and Kusza, 2019). A significant increase in the amount of pollutants deposited as a result of emissions, including Cd, Ni, and Pt, was indicated. Research conducted in the area of the Upper Silesian agglomeration revealed a significant relationship between the magnitude of magnetic susceptibility and the degree of transformation of soils, including technogenic and urban soils (Strzyszcz et al. 1994; Łukasik et al., 2015; Magiera et al., 2016a, 2016b).

Magnetic susceptibility measurements were also used to identify technogenic horizons in soil profiles. Identification of technogenic layers using magnetometric methods allows for a precise indication of the transformed site in the soil profile. Such studies were carried out, for example, along the Vistula Cross-Cut, which indicated the presence of technogenic soils created during its construction (Hulisz et al., 2015; Kusza et al., 2018). Identification of technogenic layers using magnetometric methods allows for precise detection of the antropogenic horizons in the soil profile (Magiera et al., 2006).

3.2. Technogenic soils on buildings

The first modern studies of the soils formed on buildings were conducted in Toruń by Charzyński et al. (2011b), Charzyński and Hulisz (2013), and Charzyński et al. (2015a). Authors proposed a new name to classify these soils, i.e. edifisols (Latin *aedificium* = building). Edifisols are common component of urban landscapes, being a result of initial, relatively natural pedogenetic processes taking place on different constructed structures such as building's roofs, walls or gutters, bridges. They include both allochthonous material transported from the surrounding areas (e.g. dust, plants litter) and autochthonous organic material associated mainly with fresh litter from overgrowing plants. Input and accumulation of soil organic matter are very important for the formation of edifisols. Markiewicz et al. (2018) argued for the distinguishing of a new type of humus – the techno humus system – characterized by relatively low degree of humification and predominance of humic acids in the composition of humus. Edifisols were introduced as a subtype of technogenic soils in Polish Soil Classification (2019), the first national system recognizing such soils.

The other kind of soils on buildings are Technosols prepared by a human by deposition of thick layer of soil material on/over constructions made by man, such as underground garages, tunnels, as well as the above-ground bridges ("ecological passages" for animals), "green roofs", etc. Such soils, called Konstruktosols, have been introduced to the Polish Soil Classification (2019) as a subtype of technogenic soils. Studies on these soils are still in an initial phase, and only the soils developed on the military constructions (fortifications) have been documented more extensively, e.g. in Toruń and Wrocław. Typically, these soils have a coarse texture (sandy texture class), guarantying better drainage of the concrete construction, but unfavourable for vegetation due to insufficient water retention (Jankowski et al., 2013; Pardela et al., 2020).

3.3. Technogenic soils in industrial and mining areas

Technogenic soils in industrial and mining areas have been intensively investigated in Poland in recent years. As long as the past studies were focused mainly on the properties of the mining wastes in terms of their reclamation in the disposal site, at present the studies are focused on the natural functioning of the soils on dumps with emphasis on the transformations of technogenic substrate into a soil, influence of plant cover (introduced by human or from spontaneous succession) on soil properties, initiation of soil-forming and biological processes, etc. (Znamirowska-Karaś, 2002). The relatively new and rapidly growing topic are ecotoxical studies focused on soils in the contaminated industrial sites, carried out to support their remediation strategy (Karczewska and Kabała, 2017).

Previous studies related to reclamation of bituminous coal mine dumps were continued (Strzyszcz and Harabin, 2004). Moreover, studies aiming in characterization of Technosols developed on mine dumps of abandoned bituminous coal mines were also carried out by other authors, including previously omitted sites as in the Wałbrzych mining region, south-western Poland (e.g. Maciejewska and Bogda, 2003; Gwiżdż and Kabała, 2011; Gwiżdż et al., 2011; Szopka et al., 2011). At the same time, a thorough investigation of technogenic soil materials have been carried out on the burning coal mining dumps in areas of historical bituminous coal exploitation (Kruszewski, 2013; Fabiańska et al., 2016). The studies permitted, for example, for identification of unusual mineralogy of these materials, as well as the composition of organic compounds occurring on the burning dumps.

Technosols developed on the overburden heaps of open-pit lignite mines in Poland were studied in order to determine their properties, assess the advances of soil-forming processes in these soils (e.g. Znamirowska-Karaś, 2001; Wójcik, 2003; Pająk and Krzaklewski, 2006; Wójcik and Krzaklewski, 2007, 2019; Spychalski et al., 2016), and to determine the soil organic carbon stocks in soils after reclamation (Świtoniak et al., 2011; Pietrzykowski and Daniels, 2014). Numerous authors (Krzaklewski and Wójcik, 2008; Gilewska and Otremba, 2007, 2013; Pietrzykowski, 2014; Pietrzykowski and Krzaklewski, 2007; Greinert et al., 2015) noted that land reclamation of post-industrial areas have accelerated soil development.

The long-term effects of the forest reclamation of post-mining areas on the strongly acidic sands in Łęknica have been constantly under investigation. A systematic formation of pine forests has been noticed on the areas subjected to reclamation 30 years ago (Greinert et al., 2009; Greinert et al., 2013b). Along with this process, significant carbon accumulation in soils has been noted both in the litter layer and in the mineral horizon beneath (Greinert et al., 2018). The most important changes have been observed in O and A horizons due to biological activity. Authors noted that the soil forming process has still been at a very early initial stage (Greinert et al., 2013b).

Very intense studies of technogenic soils from industrial wastes produced by Zn and Pb mines were conducted in recent years, including soils on the old calamine dumps and contemporary tailing ponds (e.g. Krzaklewski and Pietrzykowski, 2002; Trafas and Eckes, 2007; Pietrzykowski et al., 2011). The research confirmed high contamination of these soils with trace elements, such as Zn, Pb, Cd, As and Tl (Cabała and Teper, 2007; Cabała et al., 2008; Jerzykowska et al., 2014). Changes of properties during the pedogenesis of Spolic Technosols driven by natural restoration of disposal sites receiving wastes from Zn and Pb ore mines in south Poland were studied by Ciarkowska et al. (2016). It was found that the contents of soil organic carbon and total nitrogen, available potassium and phosphorus including dehydrogenase activity increased with age of soils. Pedogenesis resulted also in the improvement of soil structure by the development of fine aggregates, which created porosity able to store water. Relationship between vegetation and soil properties on a dump of a historical Zn-Pb mine in Tarnowskie Góry was investigated (Pająk et al., 2018). Moreover, contamination of soils in the vicinity of the tailings ponds receiving wastes from zinc and lead mining and processing, as well as its impact on microbial functional diversity and enzyme activity in forest soils near Olkusz were studied e.g. by Krzaklewski et al. (2004), Chodak et al. (2013) and Pająk et al. (2016).

The copper ore mining and processing, beneficial for the economy of south-western Poland, also created one of the largest environmental issues for the region, related to the emissions from Cu smelters and various negative impacts of the tailing impoundments on soil environment (Karczewska et al., 2017; Kabala et al., 2020). The tailings stored in several impoundments, due to their low water capacity, low fertility, high alkalinity and high concentration of residual trace metals, are extremely unfavourable for living organisms (Chodak et al., 2005; Gawron et al., 2007; Krawczyńska et al., 2015; Kasowska et al., 2018). Thus, several attempts were undertaken to improve the tailings physical and chemical properties, aimed to accelerate their biological reclamation, using various kinds of organic substrates, including sewage sludge and geocomposites (Karczewska and Milko, 2010; Karczewska et al., 2011, 2013; Gersztyn and Karczewska, 2012; Kordas and Tasz, 2012; Spiak et al., 2012; Gersztyn et al., 2013; Marczyk et al., 2013; Kuc et al., 2019).

The studies on technogenic and contaminated soils in the areas of historical metal ore mining in the Sudeten Mountains, south-western Poland, have been continued by Karczewska and co-workers. The investigations were concentrated in the Kaczawskie Mountains (around the Żeleźniak Hill) and the Złote Mountains (Złoty Stok area), where enormous concentrations of arsenic and heavy metals are present in soils bearing the mining and smelting wastes (Karczewska et al., 2001, 2007; Karczewska, 2014). The studies focused on the solubility of arsenic and metals and the threats for human health from arsenic release to ground and surface waters and its uptake by consumable plants (Karczewska et al., 2005; Karczewska and Bogda, 2006; Krysiak and Karczewska, 2007). Moreover, solubility and toxicity of metals in the soils on mining and smelting heaps and in their surrounding was tested under artificially modified conditions, to support the selection of the most reliable and safe remediation technology (Karczewska et al., 2013; 2018; Dradrach et al., 2019, 2020a, 2020b, 2020c). The changes of selected properties of the initial soils developed on the afforested dump of copper ore mining wastes were also studied by Wójcik and Kowalik (2006). Apart from the above-mentioned studies, also concentrations of lanthanides in soils of historical mining sites in Poland were studied (Karczewska et al., 2019).

Another group of soils intensively studied in last years were the Spolic Technosols developed on mine dumps containing iron sulphides located near the abandoned Fe sulphide mines and coal mines. The studies (Uzarowicz et al., 2008; Uzarowicz, 2011; Uzarowicz and Skiba, 2011; Uzarowicz et al., 2011, 2012; Uzarowicz and Maciejewska, 2012; Uzarowicz, 2013; Uzarowicz and Skiba, 2013) allowed to determine the properties and geochemistry of these soils, and also enabled the recognition of the most important mineral transformation tracks (in particular Fe sulphide and clay minerals alterations). The research allowed to improve the definitions of the thionic horizon and sulphuric material in relation to Technosols (Uzarowicz and Skiba, 2011) in the 3rd edition of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Furthermore, on the basis of the results (Uzarowicz, 2011), supported by Charzyński et al. (2013c), the new qualifier Radiotoxic was added to the WRB classification (IUSS Working Group WRB, 2015). Fungal abundance and diversity (Stępniewska et al., 2020) and microbiological soil activity (Uzarowicz et al., 2020; Wolińska et al., 2020) as the indicators of soil development following the reclamation of the former Fe sulphide and uranium mining area in Rudki was investigated.

Also, the studies of technogenic soils developed from ash, common waste from thermal power stations, were continued in Poland in the last two decades. The effects of reclamation of a lignite combustion waste disposal site with different tree species based on field experiments were investigated (Strączyńska et al., 2004; Strączyńska and Strączyński, 2007, 2008; Krzaklewski et al., 2012; Pietrzykowski et al., 2010a, 2010b, 2013, 2018a, 2018b; Weber et al., 2015; Żołnierz et al., 2016; Gilewska et al., 2020). Organic matter properties in the topsoil layer of technogenic soils developed from ash were determined by Strączyńska et al. (2009). Carbon and macronutrient budgets under alder plantation grown on a reclaimed ash landfill were examined by Woś et al. (2020) and mercury concentration in the ash soils and in tissue of alder used to reclaim the combustion waste disposal site was determined by Woś et al. (2019). Uzarowicz and Zagórski (2015), and Uzarowicz et al. (2017, 2018a, 2018b) recognized physical and chemical properties of the Spolic Technosols developed from ash from coal and lignite combustion as the basis for soil classification. They determined morphological, physico-chemical and mineralogical indicators of Technosols transformation, as well as developed a concept of evolution of the Technosols developed from ash under existing environmental conditions.

The physical, physico-chemical and water properties, as well as ion leachability from the topsoil layer of the Spolic Technosols developed from soda industry wastes in Krakow were studied by Wójcik and Zawadzki (2011) and Boroń et al. (2016). Sutkowska and Teper (2015) and Sutkowska et al. (2015) studied Technosols developed on the old heap of wastes from soda ash industry in Jaworzno and Podzols in the surroundings of the heap. It was concluded that despite enrichment of the topsoil horizon on the top of the heap with trace elements (Cd, Cr, Ni, Pb and Zn), the current contamination of the local soils is insignificant.

Some studies were focused on technogenic soils affected by salinization and sodification in the industrial area of the Inowrocław city (Hulisz et al., 2018b). There are waste ponds where solid and semi-liquid industrial wastes produced during the manufacturing of the soda ash by the Solvay method were stored. The research revealed that eolian supply of mineral material from the soda waste ponds and locally its transport by surface water runoff can favour very high accumulation of carbonates of technogenic origin in the topsoil (over 40% $CaCO_3$ by weight). It has been also shown that despite the small acreage, these soils can be of great importance in the functioning of local habitats and ecosystems. Chemical degradation of soils has contributed, paradoxically, to the increase in biodiversity through the succession of unique and legally protected salt-tolerance plants such as *Salicornia europaea*, *Aster tripolium*, *Triglochin maritima*, *Spergularia salina*, etc. (e.g. Piernik et al., 2015).

The first symptoms of soil-forming processes and the transformation of technogenic soil properties during the natural succession and reclamation in an opencast sand quarries in southern Poland were investigated by Kowalik and Wójcik (2005), Pietrzykowski and Krzaklewski (2007), and Pietrzykowski et al. (2017). Similar studies were also conducted in northern Poland (Orzechowski et al., 2008; Smólczyński and Orzechowski 2010; Smólczyński et al., 2020). The studies showed that during technical reclamation, humus horizon was restored, as well as soil properties and soil production potential became similar to soil properties prior to exploitation.

The large attention was paid to the properties of Technosols in the sulphur mining sites (including the soils highly contaminated with sulphur) and to the assessment of the results of their reclamation (Gołda, 2003; Kowalik, 2004; Gołda et al., 2005; Woś et al., 2014; Likus-Cieślik and Pietrzykowski, 2017; Likus-Cieślik et al., 2017, 2018, 2019; Pietrzykowski and Likus-Cieślik, 2018).

Analyses of biological and ecological properties of soils in reclaimed areas were studied in recent years. Biological parameters of the soils in a former sulphur mine were investigated by Siwik-Ziomek et al. (2018) and Lemanowicz et al. (2020). The influence of tree species and faunal bioturbation on the carbon sequestration, chemical and microbial properties of the soil at three post-mining sites (Piaseczno – abandoned sulphur mine, Szczakowa – opencast sand quarry, and Bełchatów – open-pit lignite mine) afforested with pine, birch, oak, and alder were carried out by Józefowska et al. (2016, 2017, 2019), Świątek et al. (2019) and Woś et al. (2018). Moreover, Józefowska et al. (2020) investigated activity of enchytraeids as an indicator of biological reclamation of post-mining soils.

Unique chemical composition (unbalanced concentration of Mg and other nutrients, high content of Ni and Cr) and unfavourable physical properties were reported for soils developing on the dumps associated with serpentinite mining and crushing near Nasławice and Szklary, Lower Silesia, south-western Poland (Kabała and Szlachta, 2000; Karczewska et al., 2001). Kierczak et al. (2008) compared mobility of metallic elements in Technosol derived from slag after Ni-ore processing with naturally Ni-enriched peridotite-derived Cambisol in the Szklary Massif (Lower Silesia). The studies showed that mobility of metallic elements with lithogenic origin is relatively lower compared to elements with anthropogenic origin except for Ni which was more mobile in peridotite-derived Cambisol. In the other studies, it was demonstrated that the soils developed in the disposal site of slag from historical Cu metallurgy in Miedzianka (Lower Silesia) were strongly contaminated with Cu, Zn, As, and Pb (Kierczak et al., 2013). The most important factors that control pedogenesis in Cu-slag deposition site in Miedzianka and mobility of metallic elements were: (a) porosity of slag, (b) phase composition of slag that depends i.e. on the cooling rate, and (c) soil properties (pH, organic matter content).

The effect of soil organic acids on metallic elements mobilization from slag, being the parent material for technogenic soils in Miedzianka, were studied by Potysz et al. (2017, 2018). Authors demonstrated that: (a) the root exudates (i.e., citric acid, alanine, serine, glutamic acid, etc.) contribute to the mobilization of Cu, Zn, and Pb from slag to larger extent compared to fulvic and humic acids, regardless of the initial pH of the solution; (b) root exudates enhance the glass dissolution in slag compared to demineralized water, regardless of the initial pH; (c) dissolution of sulphides and fayalite is controlled by pH. It was found that the litter-derived solutions (from *Picea abies* and *Fagus sylvatica*) enhance the glass dissolution in a slag (Potysz et al., 2019). Furthermore, interactions of slags with *Acidithiobacillus thiooxidans* which mimic extremely acidic conditions on slag dump revealed relatively high metallic elements mobilization in slags (up to 92% of Zn).

Important aspect influencing pedogenesis of technogenic soils developed from industrial wastes is the mineral transformation during waste weathering. Bril et al. (2008) identified secondary minerals (i.e. gypsum, jarosite, anglesite) in the heap of slag from Zn-ore processing (Świętochłowice, Upper Silesia). Pietranik et al. (2018) applied an Automated SEM-EDS to extend the recognition of mineral phases during the slag weathering. Warchulski et al. (2019) applied a combination of methods (SEM-EDS, XRD, EM) to track the migration paths of metallic elements in slag heap in Ruda Śląska-Wirek (Upper Silesia). The study evidenced the slag weathering by the identification of secondary phases and an enrichment of effluents in metallic elements.

Other studies of Spolic Technosols in Poland in recent years included studies of geochemistry and mineralogy of technogenic soils developed on old mine heaps of abandoned iron ore mines

(Swęd and Niedzielski, 2018), as well as determination of geochemical background in soils in the vicinity of abandoned pyrite–uranium, copper, and zinc-lead mines (Gałuszka et al., 2015, 2016, 2018; Migaszewski et al., 2015).

Research in the field of environmental magnetometry, conducted in recent years in industrial areas in Poland, mainly focused on the influence of various industries on soil properties and the level of pollution in these areas. A measurable impact on degradation and formation of technogenic soils was found as a result of the emission of pollutants from the coke industry (Rachwał et al., 2015), cement industry (Gołuchowska and Wróbel, 2018), and metallurgy (Rachwał et al., 2017).

4. Future perspectives

Technogenic soils are nowadays among the most intensively studied soils. It is expected that in the nearest future the intensity of investigations will further increase. Despite a vast knowledge about Technosols, there are still many topics to develop and scientific problems to address. It seems that future studies of technogenic soils should be more interdisciplinary, complex, and should focus on functioning of these soils in the environment/landscape. Moreover, the classification of these soils should be continuously developed basing on the new knowledge which will be gained in the future.

According to the authors, the following issues should be developed in the nearest future in terms of examination of technogenic soils, not only in Poland, but also in other countries:

1) Advanced research on construction and demolition wastes and communal wastes as a parent material for technogenic soils – chemical reactivity of a different wastes, the course and the rate of weathering, taking into account various forms of deposition (admixtures, monolayers, deposits of high thickness);
2) Influence of soil property changes on the evolution of soils in industrial or mining areas;
3) Methods and techniques for improving the urban soils (especially Technosols) towards their higher water retention;
4) Methods and techniques of the protection of reclaimed soils against erosion;
5) Behaviour of plastics in soils environment, in particular in urban soils;
6) Soil mapping and spatial analysis using advanced GIS and statistical methods;
7) Genesis, directions of pedogenic processes and evolution of Spolic Technosols developed from diverse mining and industrial wastes, which should be investigated using a wide range of methods, including pedological, mineralogical, micromorphological and submicromorphological ones;
8) Genesis and evolution of Technosols in different climatic and environmental conditions;
9) Determination of indicators for quality assessment of Spolic Technosols developed from diverse mining and industrial wastes to support the remediation paths and methods, as well as to approximate their future impact on the environment and humans;
10) Health risk assessment of various types of technogenic soils;
11) Composition and transformations of soil organic matter in Technosols, also in terms of soils organic carbon sequestration in these soils;
12) Biology, microbiology, and ecology of technogenic soils, as well as interactions between anthropogenic soils substrate and biota;
13) Ecosystem services provided by technogenic soils.

5. Concluding remarks

The examination of technogenic soils, i.e. human-constructed or human-transformed soils, have a long tradition in Poland, initiated as early as in 1950s. Unfortunately, the reports of Polish researchers were in majority published in Polish, which limited spreading the remarks, ideas and solutions to the other countries. Two Polish scientists should be emphasised as the world pioneers in concepts and studies of technogenic soils: (1) Michał Strzemski, who in 1950s proposed a classification scheme for soils in urban and industrial areas, as well as listed the tasks for future studies of these soils, and (2) Tadeusz Skawina, who since 1950s successfully focused on the dynamic and directions of the soil-forming processes on the mine spoils in the context of their reclamation. Moreover, Polish researchers had great achievements in such scientific areas like (1) toxic element contamination of soils and plants in urban and industrial areas, (2) soil-forming processes in soils developed from ash and slag, (3) reclamation of mine and industrial waste disposal sites and studies of Technosols developed in such sites. Currently, the most important scientific areas, where Polish researchers have significant achievements are (4) origin, properties, functions and spatial diversity of soils in urbanized areas, (5) transformation of soils developed from different anthropogenic substrates, including reclaimed soils, (6) contamination of soils in urban and industrial areas, with emphasis on the risk assessment for humans, and (7) concepts, naming and classification of technogenic soils. Undoubtedly, the future studies will provide the knowledge necessary for reliable management of technogenic soils, considered the most common soils of the urbanized ecosystems inhabited by man.

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Badania gleb technogenicznych w Polsce: historia, współczesność i perspektywy na przyszłość

Słowa kluczowe

Gleby technogeniczne
Gleby miejskie
Gleby terenów górniczych
SUITMA

Streszczenie

Gleby występujące na obszarach silnie przekształconych przez człowieka były przez długi czas ignorowane w dyskursie naukowym. Również gospodarcze wykorzystanie tych gleb było ograniczone ze względu na ich nieproduktywność. Jedynie duże tereny pogórnicze zrekultywowane w kierunku leśnym lub rolnym były bardziej interesujące zarówno z punktu widzenia badań naukowych, jak i ich praktycznego wykorzystania. W przypadku terenów pogórniczych termin „teren bezglebowy" był używany przez długi czas, zwłaszcza w odniesieniu do terenów nie rekultywowanych. W artykule opisano historyczne badania gleb technogenicznych w Polsce (opublikowane do końca XX wieku). Gleby technogeniczne terenów miejskich i przemysłowych pojawiły się w polskich rozważaniach naukowych w drugiej połowie XX wieku. W tamtych czasach badano głównie właściwości gleby na składowiskach odpadów poprzemysłowych jako podstawę do rekultywacji technicznej i biologicznej na składowiskach. Polskimi naukowcami, których należy uznać za pionierów w kreowaniu koncepcji i badań gleb technogenicznych, są: (1) Michał Strzemski, który zaproponował schemat klasyfikacji gleb na terenach miejskich i przemysłowych, a także nakreślił propozycje kierunków badań tych gleb, oraz (2) Tadeusz Skawina, który z sukcesem skupił się na badaniach dynamiki i kierunków procesów glebotwórczych na hałdach odpadów kopalnianych w kontekście ich rekultywacji. W artykule przedstawiono również współczesne badania gleb technogenicznych (pierwsze dwadzieścia lat XXI w.). Od początku XXI wieku badania naukowe nabrały tempa. Współcześnie polscy naukowcy mają duże osiągnięcia w badaniach gleb technogenicznych, w tym w badaniu ich właściwości, genezy, ewolucji, klasyfikacji, właściwości biologicznych itp. Ponadto, w artykule nakreślono zarys przyszłych badań, które mogą być potencjalnie wykonywane w następnych latach.