

Slow-released Fertilisers: Origin of Microplastics

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Abstract: One of the main strategies for improving the efficiency of agricultural production is the use of fertilisers with slow or controlled release of nutrients, in which the granules of mineral fertilisers are covered with polymeric shells. The composition of the polymer coatings of mineral fertiliser granules with slow or controlled release of two widespread manufacturers (Brand A and Brand B), and their ability to adsorb heavy metal ions on their surface, were examined in this study. It was found that the base polymers used are the co-polymer polyethylene-polyacrylic acid in the Brand A, and polyacrylamide, polyacrylic acid and its esters in the Brand B fertiliser coating. The maximum adsorption rate of heavy metal ions on the surface of the polymer coatings with the rest of mineral filler of the Brand A and Brand B fertilisers was 54.64 and 28.74 mg/g for Cd(II) ions, 30.77 and 26.53 mg/g for Pb(II) ions respectively. Therefore, the solution to the problem of increasing the efficiency of agricultural production through the use of fertilisers with slow or controlled release of nutrients leads to environmental pollution by microplastics remaining in the soil after fertiliser application, which are also capable of adsorbing from the soil various toxic pollutants.

Keywords: microplastics; slow- or controlled-release fertilisers; polymeric coating; Cd(II) ions; Pb(II) ions; sustainable agriculture; nutrient management, climate change.

1. Introduction

The growing global population requires the intensification of agricultural production, one of the main sources of food. Cultivated plants require nitrogen, phosphorus, and potassium to maintain the physiological needs of their cells. Insufficient nutrient content in the soil has a negative effect on the growth of agricultural plants and leads to reduced yields. In order to increase crop yields, the doses of mineral fertilisers must be also increased. To meet the food demand of a growing population, the consumption of mineral and organic fertilisers containing nitrogen is projected to increase by 46% from 2010 levels by 2050 [1]. Each plant requires a certain amount of nutrients at different phases of its growth. However, plants assimilate no more than 40% of nutrients entering the soil with mineral fertilisers, while the remaining 60% of nutrients in the soil may pollute the environment as a result of leaching, volatilisation, and nitrification processes contributing to global warming, pollution of water streams as a result of excessive nutrient and mineral inputs causing algal growth, reduction of dissolved oxygen concentration, loss of biodiversity, and changes in the biogeochemical properties of the soil [2, 3]. As a result, low nutrient uptake by agricultural plants contributes to environmental pollution, and reduces the economic efficiency of agricultural production by increasing the consumption

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of mineral fertilisers [4–6]. Furthermore, the use of mineral fertilisers in significant quantities, in particular urea, can lead to significant greenhouse gas emissions [7], which is restricted by current international agreements. Furthermore, most countries allow a certain amount of plastics in fertilisers; for example, Germany allows plastic content of up to 0.1 weight % (wt %). Particles smaller than 2 mm are not even counted [8]. It is therefore essential to reduce excessive use of mineral fertilisers without compromising crop productivity, which is in line with the multiple goals of sustainable agriculture.

Today, apart from targeted ~~spot~~ application of mineral fertilisers, one of the main strategies to improve the efficiency of agricultural production is the use of fertilisers with a slow or controlled release of nutrients (SRF or CRF, correspondingly). SRF and CRF production technologies allows for the inclusion of different mineral fertilisers in a granulate filler, thus obtaining complex fertilisers containing all the necessary nutrients for plants. The use of SRF/CRF enables the synchronisation of the nutrients in the soil with the needs of crops in different growth phases, which helps to reduce the dispersion of nutrients into the environment, as well as increasing crop yields [9, 10]. However, in some cases, after the application of large quantities of damaged pellets or pellets with poor quality SRF and CRF coatings, there may be an abrupt transfer of nutrients into the soil medium, which in excessive amounts may have a toxic effect on plants.

One of the ways to create fertilisers with slow or controlled release of the nutrients in the mineral fertiliser granules is by coating them with different compounds (**Figure 1**), such as inorganic (sulphur, bentonite, gypsum, and other minerals), organic (natural and synthetic polymers), and others (graphene, nanomaterials), which regulate the rate of nutrients entering the soil.

The basis of the first coatings for SRF and CRF production was sulphur. Due to the technological peculiarities of production, these coatings contained a large amount of damage, which resulted in an immediate release of nutrients upon contact with water. Mineral coatings (bentonite, gypsum, poorly soluble inorganic compounds with the general formula $\text{MeNH}_4\text{PO}_4 \cdot \text{H}_2\text{O}$, where Me is a divalent metal - Mg, Fe, Zn, Mn and others) unlike sulphur are poorly soluble in water, do not change soil pH, can improve physical and chemical properties, promoting plant growth. The prolonged effect is achieved through gradual dissolution and depends on particle size, moisture, soil acidity, and temperature. Unlike inorganic coatings, synthetic organic polymeric materials (polyethylene, acrylic polymers, polyurethane, and others) are insensitive to environmental influences. The rate of nutrient release is determined by the thickness of the coating, the presence and size of pores in the coating, and soil temperature, which have a significant effect on their diffusion. However, the use of synthetic, hard-to-degrade polymers as coatings leads to the accumulation of plastic particles in the soil. Thus, the application of such SRF/CRF becomes a source of soil contamination by microplastics (MP). In this regard, much attention is paid to the development of biodegradable coatings based on natural polymeric materials (starch, cellulose, agricultural waste, lignin, and others). Since, in their pure form, natural polymeric materials do not have sufficient mechanical strength, they are used in combination with other polymeric materials. A modern trend in SRF and CRF production is the use of nanotechnology to create a physical barrier by coating fertiliser granules with a specific membrane or hydrophobic polymer having pores filled with nanoparticles [11–13].

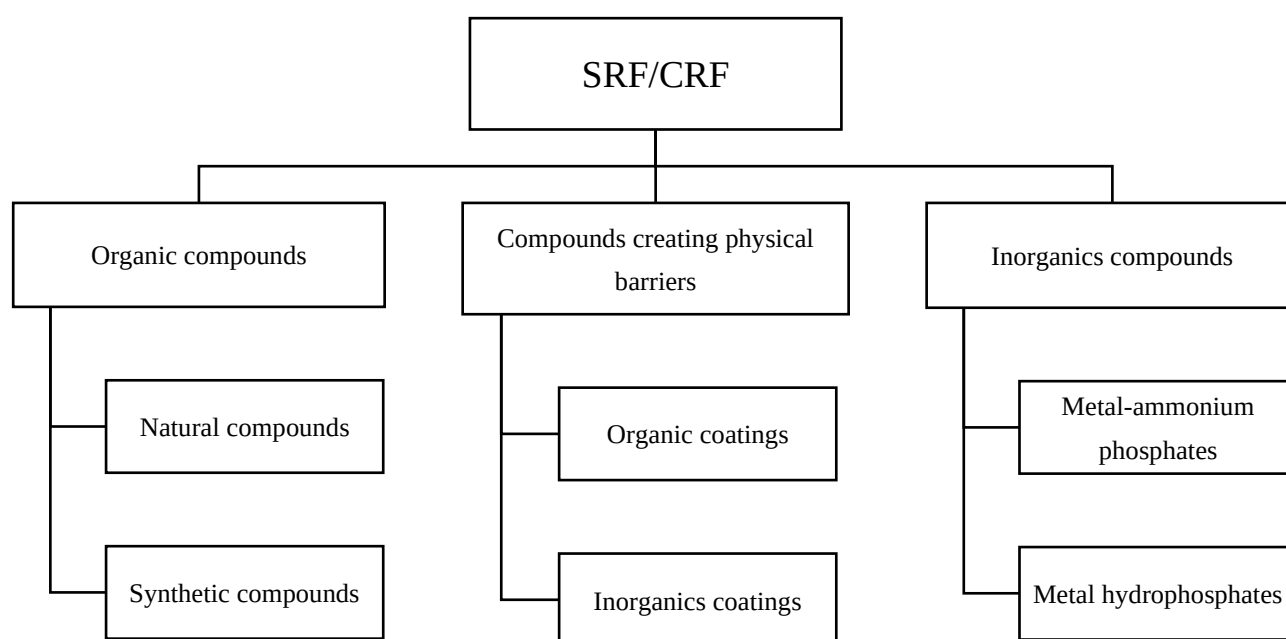


Figure 1. Classification of materials used to produce SRF/CRF.

However, for the production of SRF/CRF on an industrial scale, in most cases mineral granules are covered with polymer shells made of the cheapest inert hydrophobic materials available (i.e. polyethylene, acrylic polymers, polyurethane and their copolymers), materials which are not susceptible to biodegradation in the natural environment, which leads to environmental MP pollution [14–17]. Despite the fact that MP studies in soil are actively ongoing, there is as yet no definitive answer to the question of the real danger of MP in soil on human health, and there are already noteworthy results about both the ingress of MP particles from agricultural soils into human food [18], and the negative impact of its presence on physical, chemical, and biological properties soils, crops [17, 19, 20]. Moreover, soil is currently considered to be the main environmental medium in which MP particles are accumulating: the annual MP pollution of soils is estimated to be between 4 and 23 times higher than that of the oceans [21].

Therefore, the purpose of this study is to investigate the composition of polymer coatings in SRF/CRF, as well as to estimate the possible adsorption on their surface of heavy metal ions as typical examples of toxic pollutants present in the soil [22].

2. Materials and Methods

The widely used SRFs/CRFs of Brand A and Brand B were selected for the study, the main characteristics of which are presented in **Table 1**. Brand A 6M and Brand A 12M fertilisers are homogeneous granules of nutrients uniformly coated with a flexible polymer that controls water penetration and therefore the dissolution of nutrients within the coating. The prolonged effect of the fertiliser is achieved by varying the thickness of the polymer coating, which determines the rate of water penetration into the granule and the diffusion of dissolved nutrients into the soil. Brand A 6M and Brand A 12M fertilisers are recommended for use in substrate mixtures, horticulture, nurseries, and fertilisation of planting pits. Brand B 2–3M, Brand B 5–6M and Brand B 8–9M are complex mineral fertilisers based on compounds of nitrogen, phosphorus, and potassium with prolonged action, which is achieved by a multi-layer porous polymer coating. When applied to the soil, water penetrates through the pores into the granule, causing it to swell, and through the enlarged pores, diffusion of dissolved nutrients into the soil takes place. Brand B 2–3M, Brand B 5–6M and Brand B 8–9M are recommended for use in pots, containers, or beds for ornamental plants, flowers, and agricultural crops.

Table 1. Base characteristics of SRF/CRF under study according to manufacturer specifications

Product Name	Time of exposure, months	Granule size, mm	Macronutrient content						
			N _{tot} , %	N _{NO3-} , %	N _{NH4+} , %	P ₂ O ₅ , %	K ₂ O, %	MgO, %	S, %
Brand A 6M	5-6	2,5-3,5	15,0	7,0	8,0	8,0	12,0	2,0	5,0
Brand A 12M	10-12	2,5-3,5	15,0	7,0	8,0	8,0	12,0	2,0	5,0
Brand B 2-3M	2-3	1,5-2,0	12,0	5,3	6,7	7,0	18,0	-	-
Brand B 5-6M	5-6	1,5-2,0	19,0	6,2	8,2	9,0	10,0	2,0	-
Brand B 8-9M	8-9	1,5-2,0	11,0	4,3	6,3	11,0	18,0	-	-

The polymer coatings of selected the SRF/CRF were separated from the fertiliser granules, washed with distilled water, and dried (Figure 2). To determine the composition of the polymer coatings used and to further study the adsorption of heavy metals on them, the polymer coatings of selected SRF/CRF were separated from the fertiliser granules, washed with distilled water and dried (MP of Type 1) (Figure 2). To check how the fertiliser residues affect the adsorption of heavy metals, a more thorough removal of mineral filler from the surface of the SRF/CRF polymer coatings was carried out by additionally washing them with large amounts of distilled water heated to 60°C (MP of Type 2) (Figure 3).

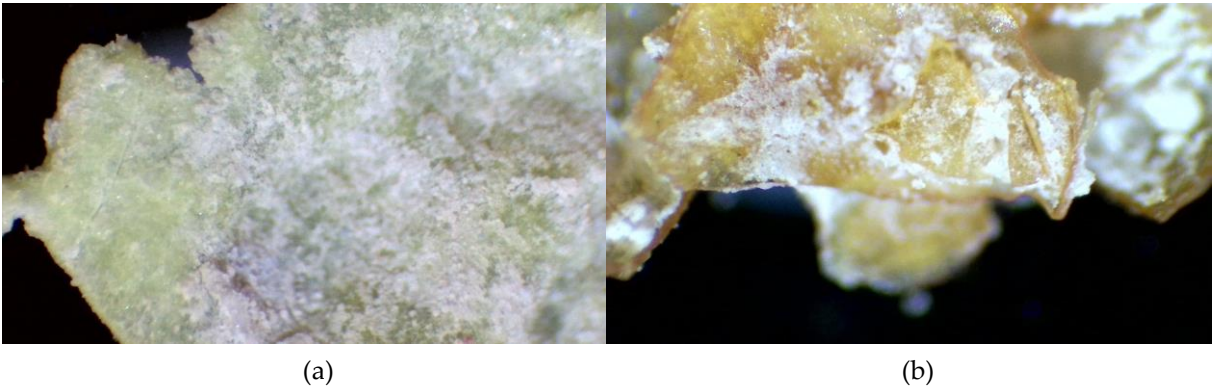


Figure 2. Typical pictures of Type 1 polymer coatings of Brand A and Brand B SRF/CRF at 10x magnification: Brand A 6M (a) and Brand B 5-6M (b).

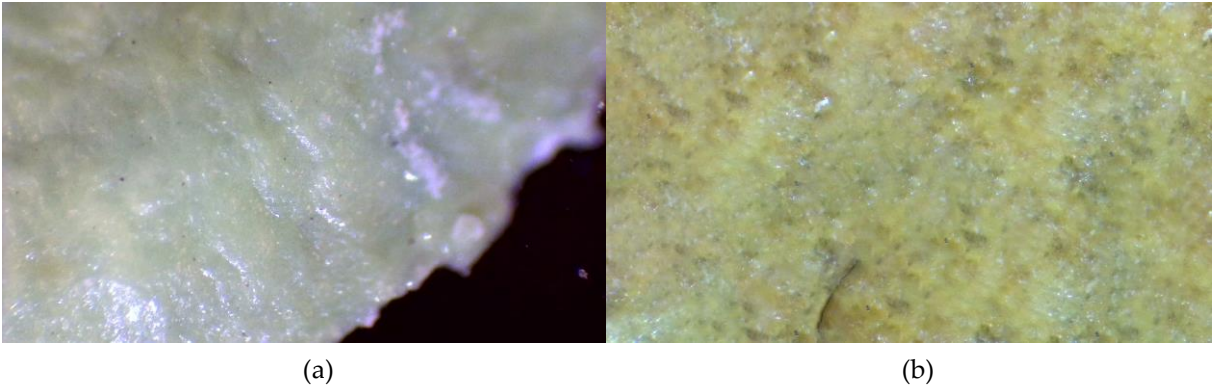


Figure 3. Typical pictures of Type 2 polymer coatings of Brand A and Brand B SRF/CRF at 10x magnification: Brand A 6M (a) and Brand B 5-6M (b).

The composition of the polymer coatings was determined using infrared spectroscopy. The spectra were recorded on a Bruker Vertex 70 FT-IR spectrometer at a resolution of 2 cm⁻¹, the number of scans was 30, using a Pike single broken total internal reflection micropiece with a working element made of ZnSe.

The composition of the mineral filler remaining on the surface of the polymer coating was determined using X-ray diffraction. Diffractograms were registered on DX-27mini X-ray diffractometer made by HAOYUAN INSTRUMENT using the following parameters: initial angle 20°, final angle 50°, step 0.03°, seconds per step 0.2, voltage 40 kV, current 15 mA.

Cd(II) and Pb(II) ions were chosen to study the adsorption of heavy metal ions on the surface of polymer shells because they are among the priority soil pollutants due to their rapid rate of accumulation in soils as a result of anthropogenic human activities (mining, metallurgical and chemical industries, use of fertilisers and pesticides in agriculture, etc.) and high toxicity to the environment, plants, animals and human health [23, 24].

Adsorption of Cd(II) and Pb(II) ions, was studied under static conditions from 100 cm³ model solutions with Cd(II) and Pb(II) ion concentrations of 1, 10, 25, 50 and 100 mg/dm³, which were intensively stirred with 0.1 g of polymer coatings until the adsorption equilibrium was established. The concentration of Cd(II) and Pb(II) ions in model solutions was determined by atomic absorption spectrometry on a Lumex MGA spectrometer with electrothermal atomisation of the sample and high-frequency Zeeman correction of non-selective absorption. Electrode-free discharge lamps with higher intensity compared to traditionally used lamps with hollow cathodes were used as the radiation source, which allowed to reduce the detection limits of Cd(II) and Pb(II) ions. The maximum temperature of sample atomisation is 3000 °C. The high-purity argon flow rate is 2 litres/min, and the spectral range is 190–900 nm. The cooling system is closed and based on water.

The equations of the Langmuir (1) and Freundlich (2) adsorption theories were used to treat the isotherms of adsorption of Cd(II) and Pb(II) ions by the surface of polymer coatings:

$$q_e = \frac{q_{max} * K_L * C_e}{1 + K_L * C_e} \quad \frac{1}{q_e} = \frac{1}{q_{max}} + \frac{1}{q_{max} * K_L} * \frac{1}{C_e} \quad (1)$$

$$q_e = K_F * C_e^{\frac{1}{n}} \quad \ln q_e = \ln K_F + \frac{1}{n} * \ln C_e \quad (2)$$

where q_e is the ion adsorption equilibrium value, C_e is the equilibrium ion concentration in the model solution, q_{max} is the ion adsorption limit value, K_L and K_F is the Langmuir and Freundlich adsorption equilibrium constant, and correspondingly, $1/n$ is the adsorption index. The linear dependence of the adsorption isotherms confirms the legitimacy of the application of these equations [25–27].

The linear dependence of adsorption isotherms in the linear coordinates of the equations of adsorption theories is a prerequisite for proving the validity of these equations.

3. Results

The infrared spectra of the polymer coatings of Brand A and Brand B SRF/CRF are presented in Figure 4.

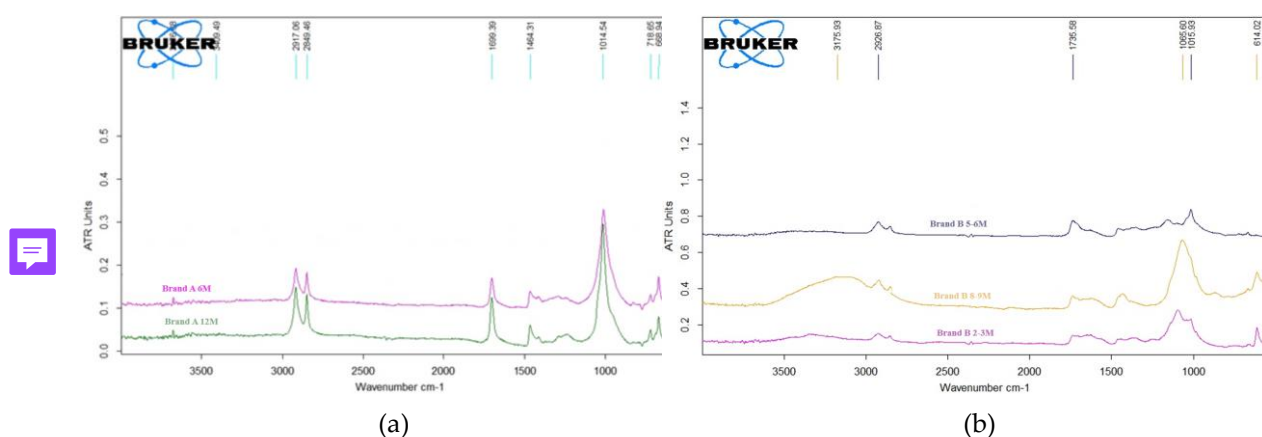


Figure 4. Infrared spectra of the polymer coatings of Brand A (a) and Brand B (b) SRF/CRF.

Infrared spectra of the Brand A polymer coatings showed the presence of absorption bands related to vibrations of methylene groups of polyethylene in the region of 2930–2850 cm^{-1} , 1464 cm^{-1} , 719 cm^{-1} and absorption bands related to vibrations of the carboxyl group of polyacrylic acid (3400 cm^{-1} - vibration of the OH-group and 1700 cm^{-1} - vibration of the C=O group). Hence, it can be concluded that the base polymer in the coating is a polyethylene-polyacrylic acid copolymer.

Polyacrylamide, polyacrylic acid and its esters (acrylates) are present in the polymer coatings of Brand B SRF/CRF, which is confirmed by the presence of absorption bands on infrared spectra associated with symmetrical valence vibrations of the N-H amide group (3176 cm^{-1}), valence vibrations of methylene groups (2927 cm^{-1}), valence vibrations of the C=O carboxyl group (1736 cm^{-1}), and valence vibrations of the C-O-C group (1066 cm^{-1}).

Diffraction patterns of mineral filler remaining on the surface of the polymer coatings studied are rather similar for each product. Typical diffraction patterns are shown in **Figure 5**.

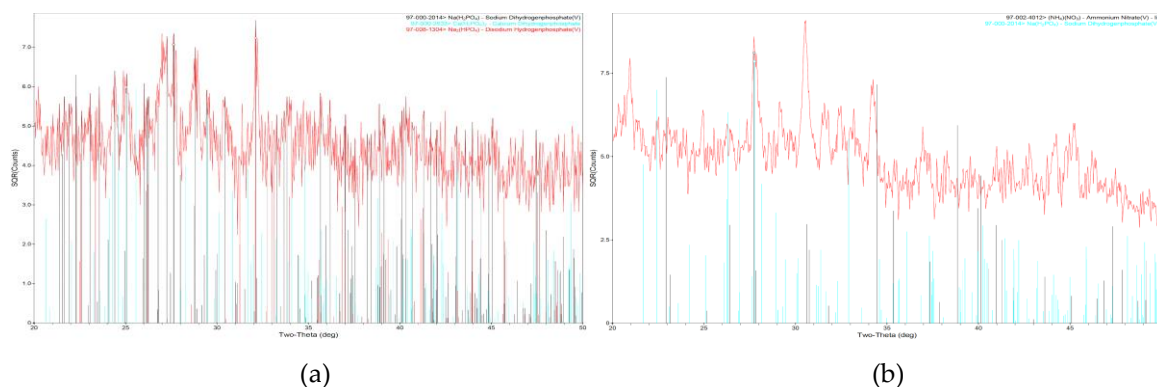


Figure 5. Diffraction patterns of mineral filler remaining on the surface of studied Type 1 polymer coatings of Brand A 6M (a) and Brand B 5-6M (b) SRF/CRF.

Analysis of these diffraction patterns revealed the presence of sodium and calcium hydro/dihydrophosphates on the surface of the polymer coatings of the Brand A fertilisers, and particles of sodium dihydrophosphate and ammonium nitrate on the surface of the polymer coatings of the Brand B fertilisers, which can influence the adsorption of pollutants present in the soil.

The adsorption isotherms of Cd(II) and Pb(II) ions by the surface of the polymer coatings of Brand A 6M and Brand B 5-6M SRF/CRF are presented in **Figures 6** and **7**.

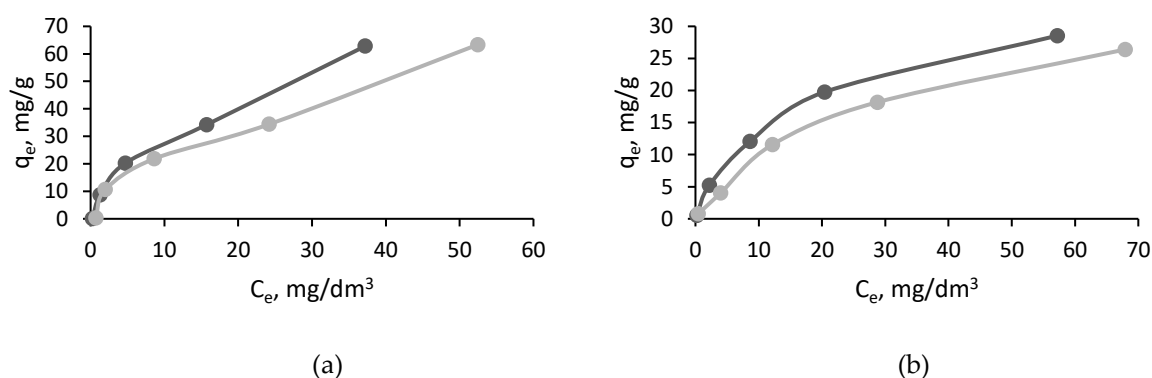


Figure 6. Adsorption isotherms of Cd(II) ions by the surface of the polymer coatings of Brand A 6M (a) and Brand B 5-6M (b) SRF/CRF (dark grey curves correspond to Type 1 polymer coatings, light grey curves correspond to Type 2 polymer coatings).

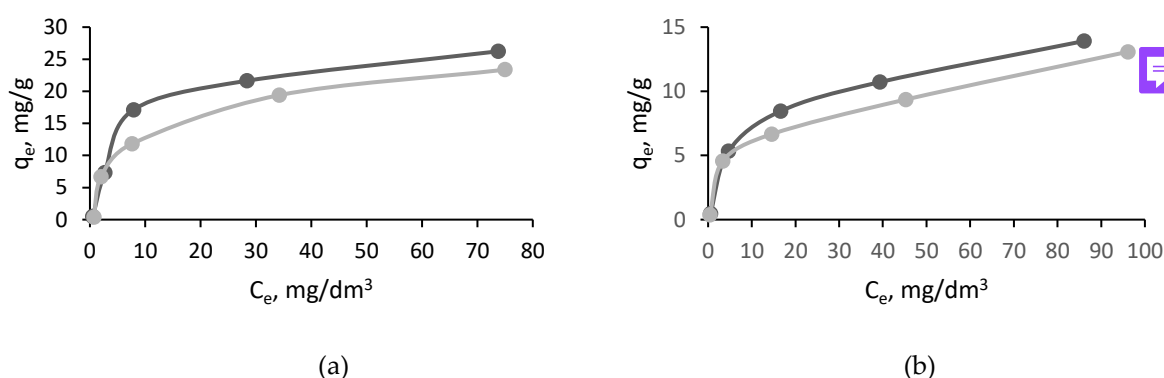


Figure 7. Adsorption isotherms of Pb(II) ions by the surface of the polymer coatings of Brand A 6M (a) and Brand B 5-6M (b) SRF/CRF (dark grey curves correspond to Type 1 polymer coatings, light grey curves correspond to Type 2 polymer coatings).

The adsorption isotherms of Cd(II) and Pb(II) ions by the surface of Type 1 polymer coatings of the mineral fertiliser granules of Brand A 6M and Brand B 5-6M SRF/CRF in linear coordinates of the Langmuir (a) and Freundlich (b) adsorption theory equations are shown on **Figures 8-11**.

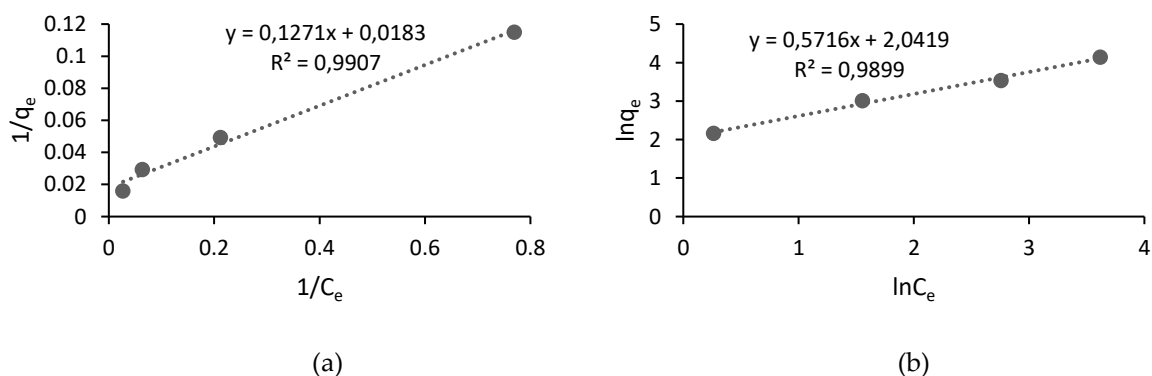


Figure 8. Adsorption isotherms of Cd(II) ions by the surface of Type 1 polymer coatings of mineral fertiliser granules of Brand A 6M SRF/CRF in linear coordinates of the Langmuir (a) and Freundlich (b) adsorption theory equations.

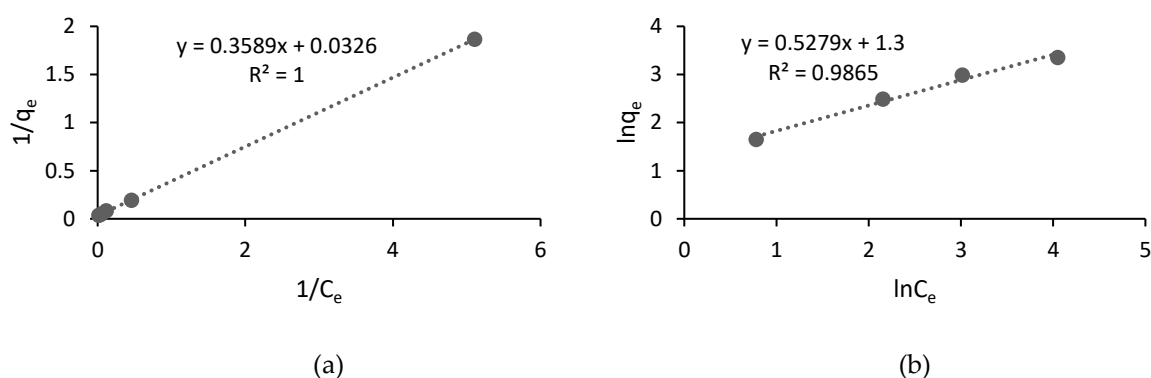


Figure 9. Adsorption isotherms of Cd(II) ions by the surface of Type 1 polymer coatings of mineral fertiliser granules of Brand B 5-6M SRF/CRF in linear coordinates of the Langmuir (a) and Freundlich (b) adsorption theory equations.

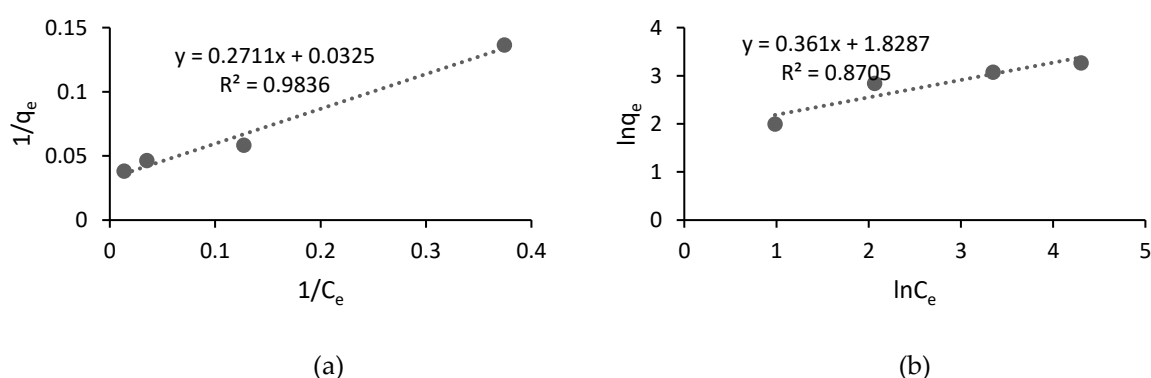


Figure 10. Adsorption isotherms of Pb(II) ions by the surface of Type 1 polymer coatings of mineral fertiliser granules of Brand A 6M SRF/CRF in linear coordinates of the Langmuir (a) and Freundlich (b) adsorption theory equations.

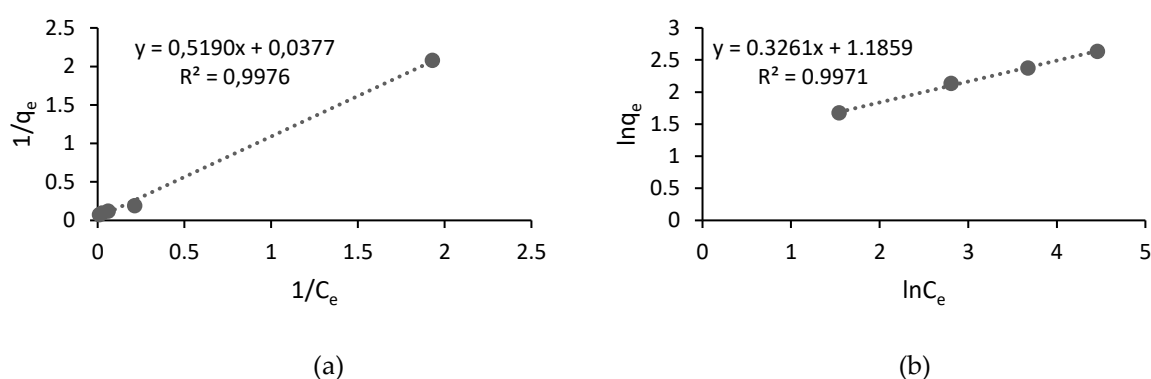


Figure 11. Adsorption isotherms of Pb(II) ions by the surface of Type 1 polymer coatings of mineral fertiliser granules of Brand B 5-6M SRF/CRF in linear coordinates of the Langmuir (a) and Freundlich (b) adsorption theory equations.

Analysis of the data obtained shows that both adsorption theories perfectly describe the adsorption of Cd(II) and Pb(II) ions by the surface of the polymer coatings of the SRF/CRF examined. The values calculated for the constants in the equations of the Langmuir and Freundlich adsorption theories are presented in **Tables 2 and 3**.

Table 2. Constants in the equations of the Langmuir and Freundlich adsorption theories describing the adsorption of Cd(II) ions by the surface of Type 1 and Type 2 polymers coatings of Brand A and Brand B SRF/CRF.

Type of SRF/CRF	Langmuir equation		Freundlich equation	
	$q_{\max}$, mg/g	K_L , dm ³ /mg	K_F , mg/g*(dm ³ /mg) ^{1/n}	1/n
Brand A 6M (Type 1)	54,64	0,14	7,71	0,57
Brand A 6M (Type 2)	47,85	0,15	7,14	0,53
Brand B 5-6M (Type 1)	28,74	0,10	3,67	0,53
Brand B 5-6M (Type 2)	22,02	0,11	2,54	0,50

Table 3. Constants in the equations of the Langmuir and Freundlich adsorption theories describing the adsorption of Pb(II) ions by the surface of Type 1 and Type 2 polymers coatings of Brand A 6M and Brand B 5-6M SRF/CRF.

Type of SRF/CRF	Langmuir equation		Freundlich equation	
	$q_{\max}$, mg/g	K_L , dm ³ /mg	K_F , mg/g*(dm ³ /mg) ^{1/n}	1/n
Brand A 6M (Type 1)	30,77	0,12	6,23	0,36
Brand A 6M (Type 2)	25,22	0,13	5,75	0,34
Brand B 5-6M (Type 1)	26,53	0,07	3,27	0,33
Brand B 5-6M (Type 2)	21,14	0,08	2,81	0,31

Analysis of the data obtained shows that the limiting values of the adsorption of Cd(II) ions by the surface the of Brand A and Brand B SRF/CRF polymer coatings (Type 1) are 54.64 mg/g and 28.74 mg/g respectively, and of Pb(II) ions by the surface of the Brand A 6M and Brand B 5-6M SRF/CRF polymer coatings are 30.77 mg/g and 26.53 mg/g respectively. The limiting values of Cd(II) ions adsorption by the surface of SRF/CRF polymer coatings (Type 2) of Brands A and B are lower (47.85 mg/g and 22.02 mg/g, respectively) compared to the worse-washed samples (Type 1). A similar picture is observed for the adsorption of Pb(II) ions on the surface of SRF/CRF polymer coatings Brand A 6M and Brand B 5-6M (type 2), which is 25.22 mg/g and 21.14 mg/g, respectively.

4. Discussion

In the present study, we found that the polymer coatings of Brand A SRF/CRF granules are based on a polyethylene-polyacrylic acid copolymer. For Brand B SRF/CRF, these polymers are polyacrylamide, polyacrylic acid, and its esters.

Polyethylene is an inert hydrophobic material consisting of long carbon chains, which makes it rather stable for biodegradation in natural conditions. High hydrophobicity and a small specific smooth surface prevent the formation of biofilms by polymer-degrading microorganisms. In addition, the catalytic properties of enzymes secreted by microorganisms are incompatible with the inert, hydrophobic surface of polyethylene. The resistance to biodegradation of polyethylene decreases as a result of photodegradation and/or chemical degradation, as well as when it is modified with starch and pro-oxidant additives. All polyethylene films and coatings may contain a stabiliser that prevents oxidation. Attempts to add pro-oxidants (i.e., stearates of transition metals such as iron, manganese, titanium, and cobalt) in polymer coatings promote radical reactions and cleavage of the polymer chain, making it more accessible for biodegradation under certain conditions by some Gram-negative and Gram-positive bacterial species, belonging to the genera *Pseudomonas*, *Ralstonia*, *Stenotrophomonas*, *Klebsiella*, *Acinetobacter*, *Rhodococcus*, *Staphylococcus*, *Streptococcus*, *Streptomyces*, *Bacillus*, etc. [28, 29]. Polyacrylic

acid, polyacrylates, polyacrylamide, and polyacrylonitrile are the most widely used substances for the manufacture of SRF/CRF polymer coatings based on acrylic polymers in the coating of Brand B SRF/CRF. When assessing the biodegradability of acrylic polymers, it is necessary to take into account the polymer structure (hydrocarbon chain length, presence of side functional groups, presence of quaternary carbon atoms, and spatial molecular organisation) and the ability of microorganisms to form biofilms on the surface of acrylic polymers under natural conditions. Some species of microorganisms are capable of biodegrading certain types of acrylic polymers. The biodegradation process of acrylic polymers proceeds in two stages. At the first stage, side groups— amide, nitrile, or alkyl — are detached from the hydrocarbon chain under the action of hydrolytic enzymes and linked by ester bonds. To describe the second stage of hydrocarbon chain biodegradation, several pathways have been proposed: an aerobic pathway of biodegradation based on propionic acid metabolism carried out by cell-free extracts of *Propionibacterium shermanii* and an anaerobic pathway of hydrocarbon chain biodegradation under the action of amidases and other enzymes. Although some microorganisms are able to degrade acrylate monomers, biodegradation of acrylic polymers is inefficient, especially at high concentrations [30, 31].

The data obtained confirm the results of earlier studies [32, 34], which showed that polymer coatings based on synthetic non-biodegradable polymers are often used for SRF/CRF industrial production. Moreover, these polymer coatings may adsorb different hazardous substances.

When using SRF/CRF, mineral fertiliser particles may remain on the inner surface of the polymer coating shell, which is confirmed by the analysis of diffractograms of the mineral filler remaining on the surface of the Brand A and Brand B SRF/CRF polymer coating shells after washing with distilled water. Particles of mineral fertiliser remaining on the surface of polymer coatings can act as additional active centres in the adsorption of pollutants. This is confirmed by higher value of adsorption of Cd(II) and Pb(II) ions on the surface of polymer coatings, which are worse washed from fertiliser residues, compared to those of Cd(II) and Pb(II) ions on the surface of better washed polymer coatings.

The results of Cd(II) and Pb(II) ions adsorption by the surface of the polymer coating shells of Brand A 6M and Brand B 5-6M SRF/CRF are similar to the conclusions obtained previously [35, 36], that the Langmuir and Freundlich adsorption theories perfectly describe the adsorption of these ions on polymers, and that the Langmuir adsorption theory fits better than the Freundlich one (**Tables 4, 5**). Moreover, the values of the adsorption limit of Cd(II) and Pb(II) ions in the present study are comparable to those reported in [35, 37], and significantly higher than those reported in [35]. These differences can be explained by differences in the polymers (polyethylene-polyacrylic acid copolymer, polyacrylamide, polyacrylic acid and its esters in Brand A and Brand B SRF/CRF versus low-density polyethylene produced by Dongming Plastic Material Co. Ltd in [34], polyethylene collected from beaches and sediments in South West England in [35] and Sigma Aldrich polyethylene in [36], with different surface properties and particle sizes considered.

Table 4. Adsorption parameters of Cd(II) ions by polymer coatings measured in the present study and reported previously in refs [36] and [37].

Adsorption theory	Parameters	Brand A (Type 1)	Brand A (Type 2)	Brand B (Type 1)	Brand B (Type 2)	HDPE [36]	PE [37]
Langmuir	$q_{\max}$, mg/g	54,64	47,85	28,74	22,02	30,49	0,10
	K_L , dm ³ /mg	0,14	0,15	0,10	0,11	0,74	0,14
	R^2	0,9987	0,9931	1,000	0,9956	0,9347	0,8700
Freundlich	K_F , mg/g*(dm ³ /mg) ^{1/n}	7,71	7,14	3,67	2,54	6,93	2,00
	1/n	0,57	0,53	0,53	0,50	0,53	0,58
	R^2	0,9928	0,9868	0,9865	0,9884	0,9206	0,8300

Table 5. Adsorption parameters of Pb(II) ions by polymer coatings measured in the present study and reported previously in refs [38] and [37].

Adsorption theory	Parameters	Brand A (Type 1)	Brand A (Type 2)	Brand B (Type 1)	Brand B (Type 2)	PE [36]	PE [37]
Langmuir	$q_{\max}$, mg/g	30,77	25,22	26,53	21,14	39,95	0,72
	K_L , dm ³ /mg	0,12	0,13	0,07	0,08	0,50	0,44
	R^2	0,9836	0,9895	0,9976	0,9954	0,9970	0,9100
Freundlich	K_F , mg/g*(dm ³ /mg) ^{1/n}	6,23	5,75	3,27	2,81	2,44	2,14
	1/n	0,36	0,34	0,33	0,31	0,24	0,47
	R^2	0,8705	0,9783	0,9971	0,8872	0,9220	0,9000

The low K_L value for the adsorption of Cd(II) and Pb(II) ions by the surface of the polymer coatings of Brand A 6M and Brand B 5-6M SRF/CRF enables us to conclude that the affinity of adsorbent to adsorbent is rather low. The value of $1/n < 1$ leads to the conclusion that the interaction of adsorbent ions with each other is weaker than the interaction of adsorbent with adsorbat.

The results of the study indicate that polymer coatings can accumulate Cd(II) and Pb(II) ions in soil. The adsorption and desorption processes of Cd(II) and Pb(II) ions can change the toxicity of both pollutants, making them more bioavailable in soil for polymer coating particles, which can have a negative impact on plants and soil biota. This agrees with earlier studies on the MP effect on the adsorption and desorption of Cd(II) ions in agricultural soils. When MP occur in agricultural fields, the ability of the soil to retain Cd(II) ions decreases, and the mobility of Cd(II) ions in the soil increases. As a result, such microplastics become more toxic to plants and soil biota, with an increase in the probability of the accumulation of Cd(II) ions by agricultural crops and their release into groundwater [37].

5. Conclusions

According to the results obtained, we can conclude that the widely used Brand A and Brand B SRF/CRF contain non-biodegradable polymers in the coating shell, such as the co-polymers polyethylene-polyacrylic acid, polyacrylamide, polyacrylic acid and its esters (acrylates). It should be noted that even if the production and further use of such fertilisers is reduced, their widespread previous use leads to the appearance of microplastics in the soil. These polymers not only remain in the soil for a long time due to their non-



biodegradability, but also serve as significant adsorbents of various pollutants, for example heavy metals. Moreover, fertiliser residues on polymer coatings increase the adsorption of heavy metal ions. As a result, the solution to the problem of improving the efficiency of agricultural production through the use of fertilisers with a slow or controlled release of nutrients leads to environmental pollution by microplastics remaining in the soil after fertiliser application.

This should be kept in mind when creating new technologies for the development and use of fertilisers with a slow or controlled release of nutrients and research the environmental and human health hazards of microplastics, taking in mind that final decision about microplastics danger is still open.

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