Utilization of sorted secondary PET waste - raw materials in the context of sustainable development of the modern city

M S Malovanyy, S D Synelnikov, O A Nagurskiy, K M Soloviy and I S Tymchuk

Viacheslav Chornovil Institute of Sustainable Development, Lviv Polytechnic National University, S. Bandery Str., 12, Lviv, 79013, Ukraine
E-mail: myroslav.mal@gmail.com

Abstract. It is established that the lack of technologies for the complete utilization of secondary PET – raw material sorted from municipal solid waste - raw materials is a threat to the sustainable development of the modern city. One of the promising ways of PET disposal is to use it to encapsulate mineral fertilizers. Under the laboratory conditions, the technology of PET modification and capsule application to mineral fertilizer particles under fluidized bed conditions has been successfully tested. Conducted pilot tests of the release of nutrition elements from mineral fertilizers encapsulated with modified PET, confirmed the uniformity and quality of the coating. Pilot studies have confirmed the effectiveness of the new form of obtained fertilizers.

1. Introduction

Sustainable development of a modern city is impossible without successful functioning of the disposal and utilization systems of the population’s life activity products (sewage drains [1, 2], municipal solid waste [3, 4]). Recently it has become especially important for Ukraine to ensure that the municipal solid waste management system (MSW) is functioning properly. Underestimation of this aspect has often caused the destabilization of the environment, the emergence of environmental and social threats for basically all cities of Ukraine, and for some of them (Lviv, Kyiv, Ternopil) the problem has become especially acute.

The successful operation of a MSW management system is impossible without sorting separate types of waste at first, combined with the same technology of their utilization in separate containers. However, the higher MSW treatment culture, the more waste categories are sorted. But in addition to sorting, it is important to ensure that effective sorted waste utilization technologies are implemented. Traditionally known are technologies for recycling glass, metal, paper, textiles. Technologies for using the organic part of waste for biogas, composting or incineration are widely used. Problematic and not always solved (despite the seemingly simple implementation) is the problem of recycling plastic bottles made from polyethylene terephthalate (PET bottles).

Units for the primary processing of sorted PET bottles with obtaining granules or so-called «chips» are widely implemented. But this raw material does not always find a place to be used precisely because of the huge array of PET bottles that have immensely come into our lives. Even in a technically highly developed country like Japan, the recycling rate of plastic bottles is only 40%, which is not enough, especially given the huge mass of them.
Each year, the world produces around 485 billion PET products, of which 46% is for water packaging. In 2017, approximately 635 million tons of plastic waste have accumulated in the world, 79% of this waste is stored in landfills or in the natural environment, about half of which is from PET plastic products [5]. If such trends of production and waste management continue in the future, there will be about 12 billion tons of PET plastic in landfills and the environment by 2050. Annually, 25 million tons of PET waste are generated in the European Union, 26 million tons in the US, 8.8 million tons in China, and 9 million tons in Japan [6].

The urgent task is to find new technologies for the reuse of PET plastics, which together with existing technologies would help to minimize the problem. In 2018, the United Nations, in conjunction with the Ellen McArthur Foundation, announced a global commitment to the New Plastic Economy, with more than 290 signatories. This obligation encourages countries to use a cyclical economy model that closes the plastic production cycle and encourages innovation in reuse or recycling. One of these innovations, which opens large volumes of recycling of PET, is the use of it to encapsulate mineral fertilizers.

Mineral fertilizers applied into soils cannot be completely absorbed by plants, some of them get into the environment, polluting the atmosphere, groundwater and surface water. A new promising form of fertilizer is the prolonged-action fertilizer that is achieved by encapsulating traditional granular fertilizers with a water-permeable capsule. The application of the fertilizer shell (capsules) on the surface of the fertilizer’s granules reduces the process of transition of the nutrients into the soil environment, which helps to increase the coefficient of their absorption by plants. Accordingly, the required dose of mineral fertilizers, the frequency of their application, the loss of fertilizers not assimilated by plants to the environment (which leads to its contamination) etc. are reduced. Secondary PET raw material can be used as a capsule-forming material, provided that it is soluble in organic solvents, which plays a crucial role in the process of creating a film-forming composition and coating the mineral fertilizer granules. We investigated the possibility of modifying PET by implementing an alcoholysis reaction using diethylene glycol as a reagent. The result is a solubility of the modified PET in ethyl acetate, sufficient for the implementation of the process of capsule formation in the fluidized bed apparatus.

2. Physical model of encapsulation process

The encapsulation of granular fertilizers is the application on their surface of the polymer shell by the method of spraying a liquid film-forming agent onto a layer of particles. To ensure good coverage, the particles in the layer must be constantly stirred. In technologies of encapsulation of solid dispersed materials, as a rule, devices of three types are used, which are capable of providing the required mode of motion for particles: plate, drum and fluidized state [7]. During encapsulation there is a complex heat-mass transfer between the solid phase (particle surface), liquid (film-forming agent) and air. Figure 1 shows a diagram of such interaction on the example of a single particle.

The flow of heated air \( I \) contacts the solid part \( III \), on the surface of which is a solution of the film-forming agent. The result is a process of heat transfer from the gas medium to the solid phase surface, which is characterized by the coefficient of heat transfer \( \alpha \). Supplied thermal energy is spent on the evaporation of the solvent from the surface of the particle with an intensity characterized by the coefficient of mass transfer \( \beta \).

For the experimental studies we used a cylindrical apparatus of periodic action. Such devices are effective in encapsulating materials that are prone to sticking. Moving the entire cross section of the apparatus at a constant speed of air promotes a more active behavior of the particles, preventing them from sticking [7]. The film-forming solution consisted of the following components: ethyl acetate 87% (w), modified PET 10% (w), hydrolysis lignin 3% (w). Taking into account the solvent content in the film-forming agent using the mathematical model [7], the values of mass transfer coefficients were determined, the values of which for the granular mineral fertilizers studied are given in Table 1.
Figure 1. Scheme of heat-mass exchange in a system of solid body - liquid - gas during encapsulation: I - air flow that supplies heat, II - air flow that removes solvent vapors, III - solid particle, IV - film-forming solution

Table 1. The values of the coefficients of mass transfer $\beta$ during the encapsulation of granular mineral fertilizers

| Material         | Consumption of film-forming agent, $10^4\text{kg/s}$ | Amount of evaporated solvent, $10^4\text{kg/s}$ | Mass delivery coefficient, m/s |
|------------------|------------------------------------------------------|-----------------------------------------------|---------------------------------|
| Ammonium nitrate| 1.0                                                  | 0.87                                          | 0.246                           |
|                  | 3.0                                                  | 2.61                                          | 0.252                           |
|                  | 5.0                                                  | 4.35                                          | 0.256                           |
| Nitroamaphos     | 1.0                                                  | 0.87                                          | 0.195                           |
|                  | 3.0                                                  | 2.61                                          | 0.197                           |
|                  | 5.0                                                  | 4.35                                          | 0.201                           |

Based on the obtained mass delivery coefficients, the maximum consumption of $P_{\text{max}}$ film-forming agent ($10^4\text{kg/s} \cdot \text{kg of fertilizers}$) was calculated: ammonium nitrate - 20,512, nitroamaphos - 22,857. According to the obtained technological parameters, the encapsulation of granular fertilizers (ammonium nitrate and nitroamaphos) was carried out in a cylindrical apparatus of periodic action. The coverage was 10% and 20% by weight of fertilizers, which corresponds to the following average film thicknesses on the particle surface ($10^5\text{m}$): ammonium nitrate – 5.74 and 11.48; nitroamaphos – 5.23 and 10.46. The properties of the obtained fertilizers were tested experimentally.

3. Testing of encapsulated fertilizers properties
The solubility of encapsulated fertilizers was investigated experimentally by a conductometric method according to the requirements of European standard EN 13266: 2001 [8]. The results of the studies in graphical form are shown in Fig. 2.

The results obtained (Fig. 2) indicate that the kinetic dissolution curves have a predicted character, the process runs smoothly without abrupt downturns or rises. This is proof of a uniform, high-quality coating that enables the production of long-acting mineral fertilizers with the required release time.
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4. Pilot studies of encapsulated fertilizers.
Small-scale studies of the effectiveness of the use of mineral fertilizers encapsulated with modified PET were carried out using such crops as potatoes, soybeans, and maize [9]. The analysis of the results of field studies shows that in case of application of encapsulated mineral fertilizers in agroecosystems of crops such as potatoes, soybeans and maize, the rate of fertilizers nutrient elements absorption by plants is increased by an average of 4.5%. Atmospheric and hydrosphere losses in the case of encapsulated fertilizers are reduced compared to granular fertilizers from 47% to 74%. We found no dependence of nitrate content in potato tubers on the type of fertilizer applied. This indicator did not change significantly, it was much lower than the limit.

The use of prolonged-action encapsulated mineral fertilizers has shown significantly higher environmental and agronomic efficiency than granular fertilizers.

- in the case of potato cultivation, the environmental efficiency of the use of encapsulated PET mineral fertilizers is increased by 74% compared to granulated fertilizers. The application of 1 ton of active ingredient of fertilizers in a capsule form increases the yield of potatoes to 20.8 tons, whereas for granular fertilizers it is 11.5 tons.

- in the case of soybean cultivation, the environmental efficiency of the use of encapsulated PET mineral fertilizers is increased by 47.5% compared to granular fertilizers. The application of 1 ton of the active ingredient of fertilizers in a capsule form increases the yield of soybeans to 4.4 tons, while for granular fertilizers it is 1 tons.

- in the case of maize cultivation, the environmental efficiency of the use of encapsulated PET mineral fertilizers is increased by 47.5% compared to granulated fertilizers. The application of 1 ton of active ingredient of fertilizers in a capsule form increases the yield of soybeans to 7.5 tons whereas for granular fertilizers it is 4.5 tons.

The use of encapsulated fertilizers reduces the need for the active substance by 20%. The introduction of encapsulated fertilizers would reduce the production of these fertilizers by 20% and, accordingly, reduce the use of natural resources, reduce the scale of production and, accordingly, the scale of environmental pollution from these industries.

5. Conclusions.
It is established that the imperfect system of separate collection of solid waste is a significant threat to the sustainable development of the modern city, as well as the lack of technologies for full utilization of sorted waste. To a large extent, this applies to PET recyclables, with the lack of full recycling.
technologies experienced by all countries in the world. It has been established that modified secondary PET raw material can be a promising material for mineral fertilizer encapsulation. In this case, it is possible to utilize the hazardous component of the MSW and to obtain long-acting encapsulated fertilizers that reduce environmental pollution and produce a significant agro-environmental effect.

Under the laboratory conditions, the technology of PET modification and capsule application to mineral fertilizer particles under fluidized bed conditions has been successfully tested. By calculated technological parameters we obtained encapsulated film based on modified PET fertilizer with predicted characteristics. Conducted pilot tests of the release of nutrition elements from mineral fertilizers encapsulated with modified PET, confirmed the uniformity and quality of the coating, which makes it possible to obtain long-acting mineral fertilizers with the required time of release of the nutrition elements.

The analysis of the results of pilot studies of mineral fertilizers encapsulated with modified PET shows that in the case of the use of such mineral fertilizers in the agroecosystems of crops of potatoes, soybeans and maize, the absorption rate of fertilizers by plants increases by an average of 4.5%. Atmospheric and hydrosphere losses in the case of encapsulated fertilizers are reduced compared to granular fertilizers from 47% to 74%.

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