Phosphorus Recovery from Sewage Sludge Ash

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Phosphorus is an essential and limited element that cannot be replaced by any other. Phosphorus deposits in the world are rapidly depleting, so methods of recovering phosphorus from alternative sources and using it as a fertilizer in agriculture are becoming increasingly popular. Struvite from sewage sludge ash contains phosphorus, and also a significant amount of nitrogen and magnesium. It is considered an effective slow-release fertilizer that can be successfully applied to agricultural, vegetable, and ornamental crops. The slower leaching of nutrients and high fertilizer quality, and high phosphorus content can make struvite an environmentally friendly fertilizer. However, its production is not yet sustainable. The cradle-to-cradle (C2C) concept has made it possible to highlight the so-called critical points in the production of such fertilizer. Limitations are environmental (concerns about heavy metals content in sewage sludge ash), legal (standard testing, product certification, quality control), economic (cost of energy, supply-chain), legal aspects (still not implemented as a mineral fertilizer under general EU regulations) and looses during P fertilizer production.

Keywords: circular economy ; wastewater treatment ; resource recovery ; sustainability ; municipal waste ; fertilizers ; zero waste ; wet chemical extraction ; C2C

1. Introduction

The reduction of phosphorus (P) depletion is proceeding at a rapid pace and its exact date varies [1]. According to literature, this will occur within 50–370 years [2][3][4][5][6]. The distribution of phosphorus resources is uneven across the world [7][8]. Their deposits are located mainly in Morocco, accounting for approximately 70% of the total deposits. Morocco is also regarded as the largest exporter of phosphate rocks [9]. China has significant deposits of phosphates (estimated at 6% of the world's reserves) [10].

In the face of P depletion, increased demand for this nutrient, alternative sources of P are needed. Agriculture uses only limited alternative P sources. There has been only a limited experience with P recovery from wastewater combined with P reuse in agriculture. One of the critical points of a sustainable approach to P recovery and use in agriculture is the presence of heavy metals in the raw material which prevents its direct use in agriculture [11][12]. The ash produced after sewage sludge incineration (SSA) has up to 8-9 times higher in heavy metal content and can be above acceptable levels for fertilizers, compared to the raw sewage sludge [13][14]. P is not readily plant-available due to bonding in complex compounds without further processing of SSA [15][16].

It is estimated that if struvite were recovered at wastewater treatment plants globally, 0.63 million tons of P could be recovered annually, reducing phosphate mining by 1.6% [1]. Struvite is the most readily recovered compound in pilot and operational plants in Europe, the USA, China, and Japan [17]. Another critical point in the production of struvite is still unprofitable. However, the profitability of struvite production can become a reality [18] when P-fertilizers' prices rise. Struvite can be regarded as fertilizer with good quality (treated as compound fertilizer) because it contains two basic macroelements (P, N) and has relatively low solubility. The Mg content in struvite makes it an alternative fertilizer for some crops [19].

2. Phosphorus Cycle and C2C Concept as a proposition of producing sustainable products in agriculture

The cradle-to-cradle (C2C) strategy includes three main principles:

(a) waste is equivalent to food,
(b) all wastes can be treated as nutrients for subsequent product life cycles and are addressed as part of biological and technological processes,
(c) all waste should be recycled into subsequent processes [20].

The basis for applying C2C to P recovery is to convert the waste to a product that can be safely used in agriculture. The flow begins with P-rich SS, then follows with recycling treatment contributing to closing the P cycle with a certified product. For the C2C concept to be sustainable, all materials must be kept in high purity. This approach requires detailed and specific knowledge [21]. P obtained from SS should safely return to the ecosystem at the end of the cycle. The closed P cycle was discussed considering the four scopes of the C2C concept:

Scope 1: Recycling of SSA with separation of P and heavy metals (HMs) as a technological process.

Scope 2: SS thermal treatment (incineration, pyrolysis) of SS for SSA generation as a pre-treatment process.

Scope 3: P recovery from pre-treated waste with separation of HMs:

○ Sub-scope 3a: SSA recycling for P recovery as a substrate to new products,

○ Sub-scope 3b: Enrichment of the purity and elimination of HM content.

Scope 4: Development of certified products.

A major advantage of C2C is the certification of the final product, which must meet specified requirements. Certification should be viewed as a reward for achieving satisfactory quality results [22]. The C2C approach allows the integration of technology and science to provide sustainable benefits. In addition to environmental aspects, it must be characterized by high production efficiency. The most important issue of this concept relates to the zero waste" approach and minimizing the negative impact of toxic substances [21]. The C2C concept does not involve the depletion of waste resources (for example, SS), except for the material used for the construction of waste collection and storage facilities.

The most important is scope 1 as being essential for scope 4 and linked with the production of SS with different nutrient content without undesirable substances (Subscope 3a). Scope 2 comprises the transformation of SS to SSA. Incineration of SS is one of the options to generate SSA that is considered highly efficient, not always environmentally friendly but economical. The need for HMs removal from heavily polluted SS was discussed at sub-scope 3b. Scope 4 comprises the processes of technology aiming to produce final, certified products which is the most important point in the concept of a closed phosphorus cycle in agriculture.

3. Sewage Sludge to Phosphorus by Thermochemical Processes

P recovery means the recapture of this element from SS via SSA. This process can be conducted by following different methods: wet chemical extraction (for example, Sephos process, Biocon, Pash process, Eberhard process), high-temperature processes (for example, Merphec, Susan, ATZ ion bath reactor), bioleaching process (Incore) [23][24][25]. P from SSA can be recovered using thermochemical processes, which allow the transformation of ash into marketable fertilizer products according to the circular economy and C2C approach [26].

The first step is converting SS into SSA directly in incineration or co-incineration, or indirectly via SS pyrolysis before the incineration. It is constricted with solid residuals and significant differences in their composition and phosphate fertilizer values. These processes differ not only on the type of the final products, quality for agricultural use, and, more importantly, their impact on the environment.

The main product in the SS incineration is fly ash [27][28]. Incineration temperature influences the ash's properties leading to a lower P concentration in the ash fraction and greater in the volatile fraction. The combustion destroys hazardous organic compounds in the sludge and reduces unpleasant odors [29]. Dust fraction, in turn, contains contaminants captured due to the mandatory exhaust gas treatment [8]. Ash after combustion could be used as a fertilizer, however, not directly but after suitable treatment [30].

Incineration is considered to be the best available technology (BAT) [31] for SS disposal at a high temperature which can reduce the volume of material [26][32]. During incineration, P takes the form of volatile oxides, condensing upon cooling to a temperature of 400–600 °C to form P_4O_{10}, which can clog the filters [33][34]. However, the SS incineration is not a waste-free method because ash still contains HM and cannot be used directly in agriculture as this would pollute soil and impact living organisms [35].

4. Phosphorus Recovery from SSA

The central point of P circulation in C2C is its recovery in a complex process that requires appropriate plant installation, chemicals, and staff training at the very basic level. In addition, other technologies are under development and testing, while only a few technologies have been introduced in recent years. Thermochemical methods are included in the later process of P production in an electric furnace and ash calcination. The plant availability of P in SSA depended on the thermal conversion process, causing a significant change in the molecular environment of phosphates compared to the original sludge [36]. During these processes, P is transferred into a mineral form available for plants [27]. However, 18% of the P contained in the fertilizer remains in an unavailable form [37]. Obtaining P in a solid phase constitutes the basis for forming new phosphate compounds with high plant availability [2][38].

5. Fertilizers Made from SSA Closing the C2C Loop and the System of Certification

Certification procedures characterize the C2C compared to other systems aiming to support companies that produce according to C2C approaches. The C2C Certified Products Standard (now in its third version) is based on the C2C design principles established by William McDonough and Michael Braungart [39]. The following criteria are considered in the C2C certification: material health, material reuse, renewable energy, water stewardship and social fairness [39]. Companies can obtain a certification mark for their C2C product. Another critical point of the C2C concept is the lack of standard testing of such fertilizers. Sludge management faces a significant task in producing a safe fertilizer that farmers will adopt and use widely. SS should fulfill the requirements and not exceed the market prices of conventional fertilizers. Good quality, safe to handle, lack of contaminants, environmentally friendly, and competitive pricing can be attractive for farmers. The depletion of phosphate fertilizers and their high prices could additionally encourage farmers to use ash-based fertilizers.

6. Conclusions

C2C concept has the potential to save the P deposits, contribute to implementing 'zero waste' and make food production systems more sustainable. C2C closes the loop and creates more sustainable products that can be marketed based on the established certification system. Several mature technologies are operational and ready for broader adoption when the socioeconomic conditions are favorable. The concept of circular economy based on C2C reuse, recycling, and imitation of natural cycles in practice could be introduced on large scales and other critical minerals and resources. There is still a large gap between theory and practice that needs to be gradually implemented and this gap should be bridged.

References

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