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Mineralization and mobilization of biosolids phosphorus in soil: A concise review

Abubakar Musa Ahmad[1], Adamu Yunusa Ugya[2*], Habib Adamu Isah[2], Tijjani Sabiu Imam[3]

[1]Department of Biochemistry, Kaduna State University, Kaduna, Nigeria
[2]Department of Environmental Management, Kaduna State University, Kaduna, Nigeria
[3]Department of Biological Sciences, Bayero University Kano, Kano State, Nigeria

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ABSTRACT

Biosolids are the product of wastewater or municipal solid waste collected through sewerage treatment; the processes of obtaining the biosolids involve various treatment processes, which include digestion, thermal stabilization, thickening, dewatering, and drying, in order to obtain free pathogen granules. These processes undergone by wastewater in the treatment plant ultimately clean the wastewater and remove the solids which are further treated to an acceptable standard for beneficial soil amendments. The application of biosolids are considered to improve soil organic matter, moisture content, and provided essential nutrients, such as nitrogen and phosphorus in arable land as potential plant nutrients supplements for crop optimum yield. Incubation studies on the biosolids-amended soils have shown significant increases in soil phosphorus content being released as plant available P in the soil, and therefore could be a good source of phosphorus in deficient native phosphorus soil. Field-scale experiments on wheat are grown with sewage sludge have also shown yield production comparable to mineral fertilizer-treated soils. This review is thereby aimed at explaining the concept behind the mineralization and mobilization of biosolids phosphorus in soil. In this review paper, an overview of the method of preparations, origin, and sources, its application in agriculture and the environment, chemical composition, the environmental risk, soil amendments potentials of the biosolid sand regulatory, and global perspective of sewage sludge disposal all are reviewed. From the review, it was concluded that mineralization and mobilization of biosolids phosphorus in soil have beneficial input to both environment and soil nutrient amendment. It is thereby recommended that more research studies should be carried out on the mineralization and mobilization of another essential element, such as nitrogen and biochar although more research should be done with respect to mineralization and mobilization of biosolids phosphorus in soil.

1. INTRODUCTION

Biosolids are semi-solid (sewage sludge) which are generated as a result of wastewater treatment processes as represented by Figure 1 This process involves various treatment steps, including digestion, thermal lime stabilization, thickening, dewatering, and drying, in order to achieve about 99%–100% pathogen free granules (Fig. 1). Raw sludge is transferred to a primary or a series of settling tanks to enable the separation of solid particulates from the water fraction; the primary sludge is further transferred to either aerobic or anaerobic digester where organic materials are broken down to gas or incorporated into cellular biomass [1–3]. Digested sludge is then passed into the secondary digester in the presence of alkali for thickening and finally dewatered to obtain biosolids cake, while the liquid portion or water is further treated with chlorine before disposal into rivers [4–6]. These physical, chemical, and biological processes undergone by wastewater in the treatment plant ultimately clean the wastewater and remove the solids which are further treated to an acceptable standard for beneficial soil amendments, and hence termed Biosolids. These treated residuals are known to be useful as a soil amendment in agricultural fields, recreational parks, and even home gardens [7–9]. The application of biosolids are considered to improve soil organic matter, moisture content, and provided essential nutrients, such as nitrogen and phosphorus in arable land as the potential

**Corresponding Author*
Adamu Yunusa Ugya, Department of Environmental Management, Kaduna State University, Kaduna, Nigeria.
E-mail: ugya88@kasu.edu.ng

plant nutrients supplements for crop optimum yield [3,4]. Incubation studies on the biosolids-amended soil have shown significant increases in soil phosphorus content being released as plant available P in the soil, and therefore could be a good source of phosphorus in deficient native phosphorus soil. Field-scale experiments on wheat is grown with sewage sludge have also shown yield production comparable to mineral fertilizer treated soils [10,11,2].

1.1. Origin and sources of biosolids

The main sources of biosolids are derived from municipal solid waste collected through the sewerage systems by the water companies during wastewater treatment and then using different processing methods (Fig. 1) to finally obtain the desired product. Biosolids like other sources of organic waste (manure and green compost) can be applied in the soil to provide essential plant nutrients, such as phosphorus and nitrogen [12–14]. Phytoavailability of phosphorus in soil treated with biosolids is governed by several factors, including the soil characteristics and sources of biosolids phosphorus removal [15–17]. For example, biologically nutrient phosphorus removal (BNPR) produces more plant available phosphorus in soil than the chemically derived biosolids [5,6,10]. Thus, different sludge treatment processes could have an impact on mineralization characteristics of the phosphorus present when applied in the soil [18]. Phosphorus in biosolids is not necessarily as labile as P in mineral fertilizers or manure as their lability is greatly influenced by the wastewater treatment process [19–21]. Thermal drying significantly reduces P lability compared with the conventionally produced cake. The BNPR, for example, provides phosphorus uptake by microorganisms above normal levels and as such the surplus P is used for cell maintenance, synthesis, and energy transport through the conversion of wastewater P to microbial biomass P [22].

1.2. Classification of biosolids

Biosolids vary in their inorganic, readily mineralizable and recalcitrant nitrogen and phosphorus contents, which is particularly dependent on the sewage sludge treatment methods of production as well as their pathogen level. They are classified either as class A or B digested sludge.

Class A digested sludge consist of chemically or biologically treated sludges that has a level of enterococci and thermotolerant coliforms per gram of dry matter below 1000 cfu/g and is without any detection of *Salmonella* spp. [23], according to the set standard of the 40 code of federal regulation part 503 biosolids rule (Table 1), established by United States Environmental

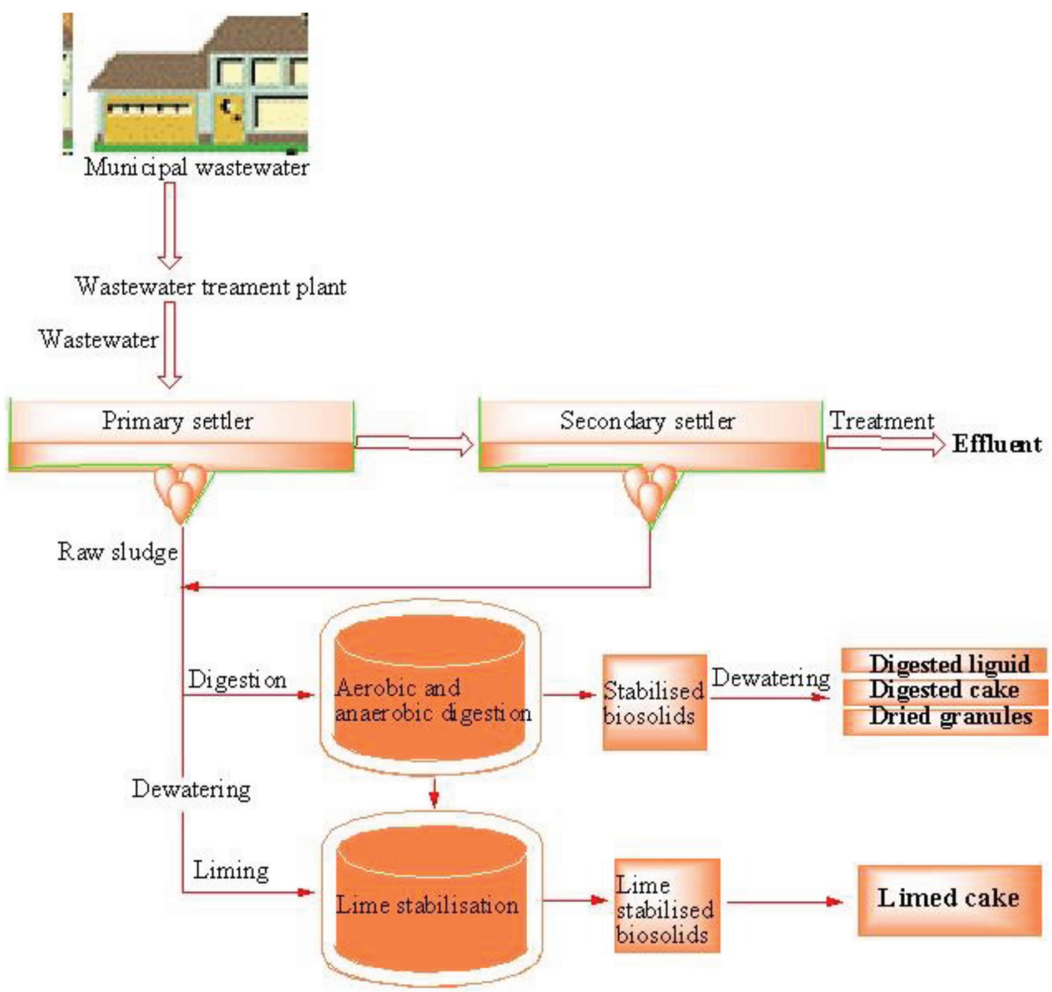

Figure 1: Production of biosolids in water industries.

Protection Agency. Class A products are suitable as fertilizer on lawns and gardens [23,24] and recommended for the application to agricultural land as it is assumed to be essentially pathogen-free [25]. In contrast, produced Class B digested sludge can contain an estimated fecal coliform density of over 1,000 cfu/g [26]. The use of Class B biosolids products are more restricted because they contain a detectable level of pathogens.

1.3. Biosolids in agriculture and environment

The beneficial use of biosolids in recycling to improve soil organic matter and crop nutrients in agriculture has increased since the implementation of the Sewage Sludge Directive 86/278/EEC by the European Union in the year 1989. As a result of the implementation of directives 91/271/EC, large amount of sewage sludge was generated by water companies in the United Kingdom and other European countries, such as Spain, Denmark, and France. Estimated annual production of over 9.4 million dry tones of biosolids is being generated by the European Union. While in the United States, over 7 million dry tones were generated by the wastewater treatment plants (WWTPs) each year and up to 60% were recycled on agricultural land [27,28]. Increase in the mineral fertilizers prices during the year 2008 (Fig. 2) in the United Kingdom have also contributed to the increased sludge production and demand for biosolids applications. Over 80% of biosolids are nowadays directly or indirectly used on land in England [29–31]. Even though the application of biosolids in agriculture and environment have beneficial effects, there have been several concerns about their short- and long-term effects on agricultural soil and environment due to the presence of potential contaminated substances such as heavy metals or other pathogens if not properly treated and could be dangerous and toxic to human health and the environment [32,33]. Nonpoint-source pollution of surface water or eutrophication by agricultural phosphorus have been a major environmental concern worldwide [34] and a significant fraction of this phosphorus mostly originated from organic waste, such as manure and biosolids used during soil amendments [35].

Table 1: Pathogen density limits.

Pathogens/indicator and class	Standard density limit (dry wt)
CLASS A	
Salmonellae	<3 MPN/4 g of total solids
Fecal coliforms	< 1,000 MPN/g
Enteric viruses	<1 PFU/4 g of total solids
Viable helminths ova	<1 PFU/4 g of total solids
CLASS B	
Fecal coliform density	<2000,000 MPN/g of total solids

MPN = most probable numbers; PFU = plaque forming units.

Biosolids like other sources of organic fertilizer can provide essential (nitrogen and phosphorus) nutrients to agricultural soil. There are different nutrient compositions of mainly phosphorus and nitrogen along with few micronutrients, such as iron, copper, and zinc [36]. The nitrogen and phosphorus contents are typically in the ranges of 2.8%–3.8% and 1.2%–3.0%, respectively [36]. The higher the quantity of available nitrogen and phosphorus is found in the dry digested cake (Table 2). However, there is a large variability in the phosphorus contents present in biosolids, depending on the treatments methods [37–39] and the relative effectiveness of biosolids-P is 50% compared to soluble fertilizer P according to the recommendations in both United Kingdom and the United States. Potassium content of biosolids is very low (0.15%–0.40%) because most of the compounds are water soluble and remains in the sewage effluent or aqueous fraction during sludge dewatering [3].

1.4. Chemical form

The chemical form of phosphorus in biosolids influences the environmental chemistry and plant availability of soil P [40–42]. Most of the biosolids-P produced through chemical treatment of wastewater during phosphorus removal is associated with inorganic iron bound (Fe-bound) or aluminum bound (Al-bound) phosphates [10]. In a greenhouse study [15], the effects of biosolids amendments on P availability in two sandy pasture soils with medium and very

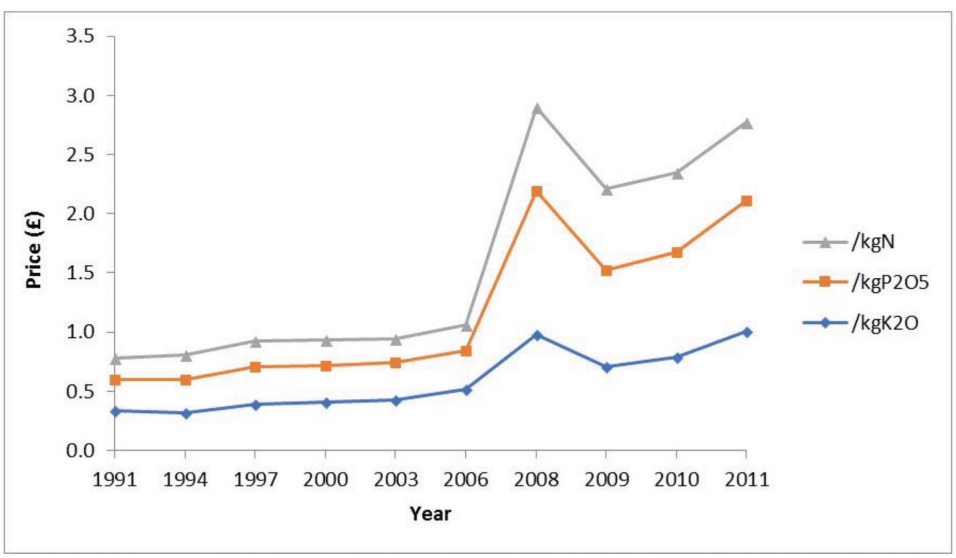

Figure 2: UK Fertilizer prices (1991–2011) nutrients composition of biosolids.

Table 2: A typical nitrogen and phosphorus content of sewage sludges.

Sludge type	Dry matter (%)	Total nitrogen	Total phosphorus	Available N	Available P
Liquid undigested (kg/m^3)	5	1.8	0.6	0.6	0.3
Liquid digested (kg/m^3)	4	2.0	0.7	1.2	0.3
Undigested cake (kg/t)	25	7.5	2.8	1.5	1.4
Digested cake (kg/t)	25	7.5	3.9	1.1	2.0

high native P content, respectively, was evaluated, 4 months after treatment, the grown cropping season bahiagrass yields did not show significance with P-sources or application rates, particularly in the very high native P soil. This was mainly due to the excessive high soil-P with high P retention capacity, as a result, it has masked the effect of biosolids added phosphorus [43–45].

1.5. Microbiology

Soil organic carbon is the main source of energy for soil microorganisms [46]. Microorganisms in the soil are able to obtain available phosphorus upon hydrolysis of organic P catalyzed by soil extracellular phosphatase enzymes. Extracellular phosphatases are those enzymes released into soil from active or non-proliferating cells, such as spores, cysts, seeds, and endospores that becomes attached to dead cells or cell debris and absorbed to clay and humic colloids that play important role in catalyzing the organic phosphorus hydrolysis reaction to release inorganic phosphorus [47]. Organic matter content in biosolids would also provide energy which could contribute toward sustaining biological activity during nutrient mineralization in soil [47]. Therefore, understanding of biological processes, such as microbial biomass carbon and enzyme activities during the mineralization of organic matter and nutrient turnover, is very important [47]. Microbial biomass is those cells of living microorganisms notably, bacteria, actinomycetes, and fungi that play vital roles in nutrient cycling and soil aggregation [48]. Biomass also functions as a sink for nutrients, such as phosphorus and nitrogen, under conditions of net immobilization depending on the state of the whole system. During a 4-year study of crop rotation system with sunflower, winter wheat, lentil, and winter wheat as the grown crops, when matured composts of vegetal and animal sources were consecutively added as a source of organic matter in soil, microbial biomass carbon was observed to increase with increase in soil total organic carbon even though other factors, such as soil moisture, pH, and temperature, could have an effect on this relationship [49,50].

Microbial phosphorus immobilization can affect P availability by removing inorganic P from soil solution particularly when soluble carbon is available for microbial growth. Phosphorus in soil interacts with other essential nutrients, such as carbon and nitrogen, in regulating biological processes and as such, the ratio of C:N:P is an important indicator for estimating carbon and nutrient fluxes during the global circulation models. Simple index measurement of the ratio of microbial biomass carbon to total organic carbon content (Cmic/TOC) is used as an indicator of carbon availability to microorganisms, conversion efficiency, losses of carbon, and carbon stabilization of soil [51]. Extracellular enzymatic activity of phosphatase showed a positive correlation with microbial biomass carbon, and the available phosphorus results were also correlated with the alkaline phosphatase activity in the matured compost treated soil [52]. The soil enzymes secreted by the microorganisms, to initially cleave or hydrolyze organic matter into smaller molecules are also potential indicators of soil quality as they play role in soil management, providing information on the biochemical processes occurring in soil [53–55]. Phosphatase enzymes activities, for example, are important during mineralization of organic phosphorus in soil [54].

1.6. Regulation and global perspectives

Disposal of sewage sludges to sea was banned by the European Union (EU) under the water treatment directive 91/271/EEC in the year 1998 [53]. This has resulted in the generation of a large amount of sewage sludges by water companies in the United Kingdom with over 9.4 million tones of dry weight produced annually in the European Union [53]. The implementation of directives and other legislative measures in the European Union concerning collection, treatment, and discharge of wastewater as well as advancement in the technological upgrading of WWTPs have caused more sludge production and even expected to increase up to 13 million tones in all EU member states by 2020 [42]. Safe disposal of biosolids is vital, as it is a major environmental concern throughout the world which presents a major challenge in the wastewater management industries [56,57]. In the United Kingdom (UK), biosolids land application and recycling is considered the best practicable options. About 80% of sludges go to land in the UK, while in the USA up to 60% biosolids are mostly recycled to agricultural soils to supply farmers with the economic alternative of chemical fertilizers.

Other disposal options include landfilling and incineration [58].

1.7. Environmental risks

Even though dewatered end products of the wastewater treatment companies are highly nutrient enriched (nitrogen and phosphorus) and amenable to use as agricultural fertilizer or as mine waste covers, they are recognized as repositories of organic pollutants and heavy metals [59]. Thus, there are public concerns of biosolids application with regards to these potentially toxic elements or organic compounds effects over time. For example, the application of biosolids to agricultural soils in excess of crop needs, when an N-based approach is used to determine land application rates, would results in the build-up of soil P, which is also amongst the direct similarity with manure and that pose significant risk to surface and groundwater during erosion and surface run-off in soil [60]. However, environmental risk of biosolids application is minimal to both humans and environment (microorganisms) if properly managed according to the strict measures and regulations by the European Union directives. Moreover, compared to manure (dairy cattle slurry), biosolids do not pose a greater risk in terms of losses along the runoff pathway in grassland soil [61].

1.8. Quantity of biosolids application in agricultural soils

There are major concerns, particularly regarding the long-term effects of biosolids application in agriculture and consequence on the soil and water quality. Biosolids are mostly applied to soil to meet nitrogen requirements in most agronomic crops with little regard to the phosphorus content, and this can result in the build-up of phosphorus in the soil [62,63]. In order to mitigate soil phosphorus, build-up, several State and Federal agencies, such as Ministry of Agriculture, Fisheries and Food and Department for Environment, Food and Rural Affairs, have recommended P-based nutrient management strategies depending on characteristics of native P of soils and other factors, such as pH, soil texture, organic matter, soil moisture content, and microbial activity [64].

1.9. Biosolids in soil

Application of biosolids to soil provides dissolved organic matter source, that causes initial degradation of decomposable fractions, accompanied by increased microbial activity in the sludge-amended soil which may lead to a priming effect that can result in concomitant decomposition of native soil organic carbon [65]. Biosolids induced positive priming effects increases the decomposition of native soil carbon as such there is an increase in the energy sources of microbial populations and subsequent increase in microbial activity in the soil [66]. Negative priming effects where decomposition of the native carbon in soil is reduced upon addition of organic residuals, such as biosolids or biochar, would instead promote the immobilization of carbon [66]. Reactions of soil, such as sorption-desorption, precipitation, or metal speciation, play critical roles in nutrient availability which often depends on the soil pH as one of the key factors [67]. Residuals from biosolids have a significant influence on solubility and speciation of soil nutrients. Buffering capacity which is the ability of soil solution to resist change in concentration of phosphorus when phosphorus is removed during plant uptake or added as fertilizer P and other amendments, such as manure and biosolids, can be an important soil characteristics controlling relationship of solid phase P and it is concentration in soil solution [68,69]. For example, temporary induced increases or decreases of soil pH upon amendments could be restored after sometimes, perhaps due to soil buffering capacity [70,71]. The solubility of iron bound biosolids-P was shown to be lower in biosolids-amended soils in terms of the P release or phytoavailability, compared to the thermally lime-stabilized biosolids or poultry litter [71].

2. CHEMICAL AND PHYSICAL PARAMETERS INFLUENCING BIOSOLIDS MINERALISATION IN SOIL

2.1. pH

Soil pH has been an important factor affecting the bioavailability of phosphorus for plant uptake.

In treated sludge, pH is a key factor toward controlling the phosphorus chemistry [72]. Application of biosolids in soil affected pH by either increasing or decreasing it depending on the initial soil pH and application rates. As a result, it affects solubility and availability of nutrients and the soil microbial activities [73]. At extreme pH (> 10 or < 4), microbial activity is inhibited and that can affect the mineralization of P in soil [74]. The dissolution and solution equilibrium reactions for the availability of inorganic phosphate in soil is largely achieved based on soil pH, phosphate minerals (iron and calcium), and their organic matter content [73]. For example, soluble phosphorus in oxides and hydroxides of aluminum or iron in the soil increases with pH levels up to about 6.5 and then, decreases significantly above the neutral pH or in high calcium phosphate compounds soils [74]. Dihydrogen phosphate ion ($H2PO4^{-}$) generally dominates at pH ranges between 2.2 and 7.2. While at 7.2–12.4 pH ranges, monohydrogen phosphate ion ($HPO4^{2-}$) are the dominant species. In calcareous soil, calcium (CaCO3) will react with phosphate ($HPO4^{2-}$) to precipitate phosphate ion [73]. The optimum pH for P availability to crops in the soil is between 6 and 7 [75]. Lowering soil pH (4.5–5.1) causes decreased soil microbial activities and can lead to subsequent changes in the substrate utilization [76,77].

2.2. Organic matter

The organic matter content presence in soil controls the dynamics of phosphorus in soil. It plays a vital role, as it affects many important soil properties [78]. For example, decomposing organic matter releases an acid that increases the solubility of calcium sulfate which causes an increase in the amount of available P. Organic matter forms two complex matrices associated with particles and other nutrients in the soil, mostly referred as coarse and fine fractions of soil organic matter [78,79]. The coarse fraction of soil organic matter (CF-SOM) is that organic material (CF > 0.4 mm) composed of un-decayed plant and animal residues and recognized as highly labile material due to fast rates of organic matter breakdown [78] In contrast, fine fraction soil organic matter (FF-SOM < 0.4mm) is considered to be more stabilize and slowly decomposing pool of soil organic material [79]. Application of organic residuals, such as manure, green compost, or biosolids, as sources of organic matter to improve soil physical, chemical, and biochemical properties has been practiced for a long time [80]. The addition of an organic substrate generally results in an increase in the size and activity of the soil microbial community as well as activities of extracellular soil enzymes [81]. The residuals from biosolids originate mainly from human feces and bacterial cells during primary and secondary sludge treatments, respectively [82]. Their organic carbon (C) ranges mostly between 20% and 50% and overall organic fraction of biosolids consist of a mixture of fats, carbohydrates, protein, lignin, amino acids, cellulose, sugars, humic materials, and fatty acids [82]. There were increases in the concentration of dissolved organic matter in soil solution following biosolids application, which subsequently decreases over time as the added biosolids organic matter decomposes [83]. Organic matter and pH in soil stimulate microbial biomass growth and this is beneficial to the majority of microbes as it provides more surface area in addition to carbon or energy sources for microbial activities such as effective nutrients degradation and mineralization [84].

2.3. Moisture content

Soil moisture is amongst one of the key controlling factors for the available phosphorus in soil. The drying and re-wetting of arable and grassland soils, therefore, have an effect on the release of biosolids-P [85]. The decrease in microbial biomass carbon with an increase in extractable phosphorus in an air-dried soil during the drying cycle was shown [85]. However, a constant microbial biomass carbon was observed with seasonal changes in microbial P content and organic P mineralization during spring and then P immobilization in the early winter months [84]. Under optimal soil moisture and temperature, a significant immobilization–remobilization sequence occurs upon addition of organic materials to soils and the pattern and dynamic of phosphorus turn over in such situation depend on the substrate, the microbial biomass (size, activity and composition), soil properties, and community structure of soil [86]. Immobilization of P in microorganisms also increases with an increase in the proportion of soluble carbon in the added substrates (biosolids) and the initial size of the microbial biomass [87].

2.4. Temperature

The solubility of phosphate ions in soil is also governed by temperature in addition to moisture content. The impacts of temperature on biosolids-treated soil phosphorus release and mineralization are minimal because phosphorus is typically immobile in most soil [36]. During a 90 days' soil incubation study by Silveira and O'Connor [88], it shows that an increase in the temperature from 20°C to 32°C has caused increased soil P retention which results in the low release of phosphorus into the soil solution. Even though the distribution of phosphorus amongst various fractions were not significantly affected by the changes in temperature. Treatments of soil with biosolids play little role in terms of differences of soil biosolids-P release or concentrations particularly in a high phosphorus content soil, or in those soil with high affinity to retain P, as it is being easily masked by P-enriched soils at the surfaces [89].

3. MINERALIZATION OF BIOSOLIDS PHOSPHORUS IN SOIL

Mineralization of P is the process by which soil microbes break down soluble and insoluble P nutrients present in organic matter through extracellular phosphatase enzymes secretion that becomes available to both plant and microorganisms [90]. Phosphorus mineralized in the soil after organic sources input of manure, such as cow dung or biosolids, is an important factor in determining overall P availability in soil [91]. Soil native P increase, during biosolids-P mineralization, may lead to modification in the distribution of P in various pools, and can subsequently increase the soil total P over time [92]. About 90% of applied phosphorus from biosolids in soil is not taken up by the plants. Rather, it is retained (locked-up) as insoluble or fixed P so that residual P can be used by subsequent growing crops [93].

3.1. Phosphorus cycle

Phosphorus is an essential element and its availability contributes to controlling some aspects of global biogeochemical processes, such as soil genesis [94]. Phosphorus cycle in the soil are generally controlled by inorganic adsorption–desorption reactions, biologically controlled mobilization and immobilization by the microbial biomass, and the native P forms, principally, whether it is in an organic or inorganic form [95]. In natural ecosystems, phosphorus is usually a scarce resource and is efficiently being recycled; whereas, in agricultural systems, P is removed in crops or animal products. Figure 3 shows phosphorus cycling in soil [94].

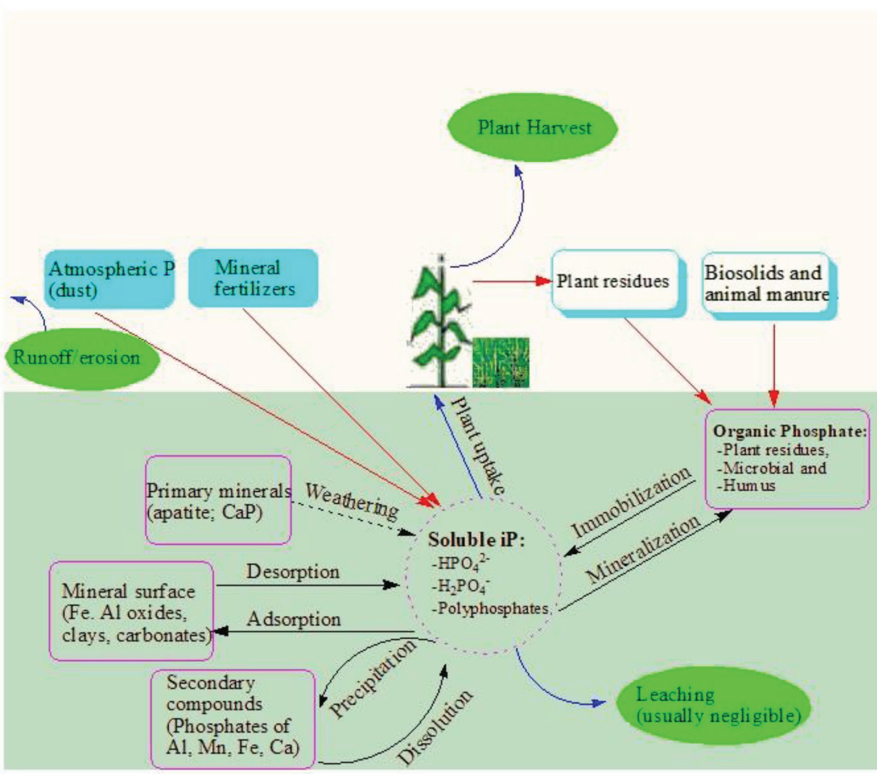

Figure 3: Phosphorus cycle in soil.

4. CONCLUSION

Phosphorus nutrients in soil organic matter are mostly present in the organic form. They are converted to inorganic forms through the process of mineralization in order to become available to crops. Phosphorus mineralization in soil is simply the release of orthophosphate during the decomposition of phosphorus nutrient containing organic materials, facilitated by extracellular phosphatase enzymes released by the soil microbes. Soil organic P is derived from the combination of plant, animal, and microbial residues and provides important P turnover during mineralization both in the organic and microbial biomass pools that form a vital component of P cycling in soil plant systems [96]. Mineralization of phosphorus in soil is partly regulated by the carbon phosphorus ratio (C:P) of substrates [97]. Carbon–phosphorus ratio (C:P) greater than 100, for example, indicates high requirements of P (1.5%–2.5% of dry weight) by soil microorganisms and as such, P would rather be immobilized by microbes. Microbes, therefore, compete with plants for available P in soil. Mineralization of phosphorus from microorganisms is also affected by the soil texture [98]. Immobilization involves the uptake of the organic forms of phosphorus into the microbial biomass and it is a reaction catalyzed by those active microbial biomass fractions in the soil in order to acquire energy [99]. Microbial immobilization of P is a vital process that provides an important source of available P, as it can often contain up to 20%–30% of the total soil organic P pool, which is even significantly higher compared to carbon (1%–2%) and nitrogen (2%–10%) proportions in the soil microbes [100]. Thus, biomass in this situation acts as a labile pool of P which is protected from fixation but is rather plant-available during biomass turnover [101]. Both mineralization and immobilization are depicted in Figures 1–3. Microbial P immobilization makes soil P temporarily unavailable to plants at some points but eventually becomes available upon complete microbial decomposition due to the simultaneous mineralization–immobilization processes during phosphorus turnover [102,103]. Due to the fact that, mineralization of soil organic phosphate pools is achieved through extracellular phosphatase enzymes activities, several factors, such as organic materials ratio (C:N:P), pH, moisture, and fertilizer P amendments affects phosphatase activities which could subsequently have effects on the organic P mineralization [104]. It is thereby recommended that more research should be done with respect to mineralization and mobilization of biosolids phosphorus in soil.

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