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# Phosphorus Opportunities and Challenges for Agriculture and the Environment in India

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Phosphorus is an important element required by all living organisms, but it is also a non-renewable resource that is only derived from mined rock phosphates. Phosphorus input is critical for food production since all plants require an appropriate quantity of it to flourish. Crop output will be reduced if there is a phosphorus shortage. Since the late nineteenth century, processed mineral phosphorus from mined phosphate rock has been employed as a phosphate fertilizer source in European agriculture. It used to increase dramatically in the twentieth century, and today, much of agricultural output on a global scale is dependent on mineral phosphate fertilizer input. Mined phosphorus is also added to livestock feeds to boost animal nutrition. Agriculture is by far the most important worldwide user of mined phosphorus, accounting for 80-90 percent of total global consumption (Childers *et al*., 2011).

Phosphorus is necessary for food production; however its usage is not without consequences. Sustainable phosphorus usage is now directly related to food security, rather than just decreasing negative environmental impacts. That is, sustainable phosphorus usage must ensure that all of the world's farmers have long-term access to adequate phosphorus to produce enough food to feed humankind while minimizing negative environmental and social impacts. While the European Union has viewed itself as a food secure zone for many decades, this paper reveals how the EU food system is in reality very vulnerable to future phosphorus scarcity. Agriculture output will be reduced if phosphorus is not present, and as a result, less food will be produced. At the moment, the EU is nearly totally reliant on imported phosphate rock, phosphorous acid, phosphorus fertilizers, and phosphorus-containing feed additives. Phosphorus rock is the world's primary source of phosphorus. It is a delectable resource. The availability of low-cost, high-quality reserves is becoming increasingly limited. The lifespan of existing good grade phosphate rock deposits is now being debated, with predictions ranging from a few decades to a few hundred years. Despite the uncertainty, there is widespread agreement that the quality of remaining reserves is deteriorating (both in terms of P2O5 content and the presence of heavy metals and other contaminants), that phosphate layers are becoming more physically difficult to access, that waste is increasing, and that costs are rising. At the same time, worldwide demand for phosphorus is predicted to rise, owing mostly to increased food consumption from a growing global population. The growing popularity of meat and dairy products (which require more phosphorus to manufacture) in developing nations, as well as phosphorus consumption for non-food applications, may drive up world demand even more.

Phosphorus (P), a critical component of DNA, RNA, ATP, and phospholipids, is required for the growth, function, and reproduction of all life on Earth. In natural ecosystems, the P lost from the soil-plant cycle system must be restored by the slow process of rock weathering, but in human-managed systems, it must be provided via fertilizer (there is no equivalent to the biological $N_2$ fixation which is only kinetically limited but potentially not resource limited). However, if animal waste or human excreta fertilization is not accessible or organized, P fertilizers are derived from non-renewable geological P deposits, which are becoming increasingly scarce (this is again in contrast to N, as N fertilizer can be produced as an endless resource via the Haber Bosch process as along as energy and natural gas is available). The one-way flow of P from mineral deposits to farms (e.g., soils), to fresh water, and eventually into oceans is already thought to be outside the safe operating zone for long-term human growth. The possible concerns of worldwide P restriction owing to peak phosphorus have recently received a lot of attention. The impending threat of such a P constraint has been partially mitigated, since it is clear that certain P resources were ignored or misclassified in the past, which will potentially endure for the next 600 years of world P supply. (Allewel *et al.*, 2020)

The report goes on to state that "over-enrichment of waters by nutrients (**Nitrogen** and **Phosphorus**) is the biggest overall sources of impairment of the nation's rivers and streams, lakes and reservoirs and estuaries."

Phosphorus from agricultural sources is seen as a significant danger to water quality. Before we can take actions to limit the amount of phosphorus entering Tennessee's rivers and streams, we must first understand how it gets there. If we understand where and how phosphorus enters our waterways, we can apply optimal management practices, which have been equated to "putting money in the bank." High soil phosphorus levels, like having a lot of money in the bank, were thought to be helpful at the time. This idea has been called into doubt in recent years owing to concerns about the link between high soil phosphorus levels and the harm to water quality posed by phosphorus-rich soil particles entering water through runoff. Soluble P from recently applied fertilizer interacts with soil surfaces, displacing other anions with lower affinity and allowing them to be absorbed (Pierzynski et al. 2005; Syers *et al.*, 2008). P sorption and desorption processes are hysteretic, with desorption rates significantly slower than sorption rates for typical soil solution P concentrations (Menezes-Blackburnetal 2018). Short-term soil P fixation is further influenced by precipitation and surface co-adsorption with metals (Hedley and McLaughlin 2005).

Soluble P levels rise to a transitory soil solution P concentration after fertilizer application, and net P adsorption and precipitation occur until equilibrium is attained. Soluble inorganic P (Pi) fixation rates in agricultural soils are typically high, and agronomic optimal levels of soil solution P may not be sustained even after one agricultural cycle. When fertilizer application is halted or reduced, solution P depletes, and the equilibrium shifts to a gradual net solubilisation and desorption of stable soil P. The rate of P desorption varies significantly various pH soils (Smith *et al.*, 2010).

## Global cycling of phosphorus

From a geochemical point of view the long-term global phosphorus cycle has four major components (Ruttenberg, 2003). (A) tectonic uplift and exposure of phosphorus-bearing rocks to the forces of weathering; (B) physical erosion and chemical weathering of rocks producing soils and providing dissolved and particulate phosphorus to rivers; (C) riverine transport of phosphorus to flood plains, lakes and oceans; and (D) sedimentation of phosphorus associated with organic and mineral matter and burial in sediments. With the elevation of sediments into weathering regimes, the cycle begins afresh. In the pre-industrial age, social production, processing, and consumption of food, feed, and fiber were spatially and temporally linked. Phosphorus taken from the soil with crops from agricultural production areas was compensated for by frequent floods or shifting cultivation, or it was replaced by phosphorus in manure from cattle grazing on nearby rangeland. Phosphorus-containing waste products (manure, agricultural residues, and human waste) were required to increase soil fertility or maintain it at levels that generated tolerable yields.

## Flows

A short description of the major P-flows in global agriculture and human hemisphere.

**A. Fertilizer P:** Beside P in animal manure, fertilizer P currently is a major input to arable soil to intensively managed grassland.

**B. Erosion and leaching:** P can be lost via erosion (mostly particle P) or leaching, and after being transported by rivers, this P finally ends up in ocean sediments. Erosion losses are comparable to crop uptake in size. In contrast to carbon, nitrogen, oxygen, hydrogen, and a few other elements, P is not a component in global ecological cycles. According to Howarth *et al.*, 1995), the term P-cycle is not applicable because substantial amounts of P are dumped yearly into the seas in the global context.

## Crop uptake, off take and recycling of crop residues

P taken up by crops comes from fertilizer P and animal dung, or it is provided by the soil (including mineralization of previously applied organic P). While some of the P taken up by crops is recycled back into the soil, the majority of it ends up in food and feed, however significant losses can occur before it reaches people or animals.

**A. Animals:** In animals, an additional phosphorus cycle develops. A considerable share of arable crops worldwide is utilized for feed, supplemented by P-additives. Phosphorus can be taken up by non-domestic animals while grazing in the wild or on rangelands.

**B. Humans:** Human phosphorus consumption does not exceed 3-4Mt P, and about the same amount is excreted. Only a portion of the phosphorus in human excreta is returned to agricultural soil.

## Phosphorus in the soil

Primary minerals, such as apatite, are the ultimate sources of phosphorus in the environment (calcium phosphate). Phosphate-bearing minerals are found in a wide range of rocks and soils. Phosphorus is released into the soil when these minerals weather. Phosphorus is a highly reactive element in the environment. Depending on the pH of the solution, it appears in solution as one of many orthophosphate forms ($PO4^{3-}$, $HPO4^{2-}$, or $H2PO4^{-}$). If orthophosphate is not immediately absorbed by plants or soil microorganisms, it will react with other soil compounds (such as calcium, iron, aluminum, and manganese), rendering it inaccessible to many plants. As a result, phosphorus has long been regarded as the limiting nutrient in many agricultural soils. The introduction of commercial, inorganic, phosphate fertilizer has corrected the inadequate availability of phosphorus in soils over the last 50 years. Phosphate fertilizer are made by collecting phosphate from rocks rich in phosphate minerals and transforming it into a form that is more readily accessible to plants. The use of relatively significant amounts of these fertilizers to agricultural soils over many decades has resulted in phosphorus buildup in many soils. Crops no longer react to extra phosphate fertilizer on those soils. This is currently true for at least half of Tennessee's agricultural soils. Soils with high phosphorus reserves typically do not have a detrimental impact on crop yields, with the exception of reducing the availability of some micronutrients such as zinc.

## Inorganic phosphorus

Inorganic P accounts for a significant portion of total P and is the primary source of P for developing plants. In Indian soils, the proportion of inorganic P in total P-content ranges from 54% to 84%. The most active forms of inorganic P are phosphorus bonded to aluminum (Al-P), iron (Fe-P), and calcium (Ca-P). The blocked and reduction-soluble forms of P are less active. These forms exist in all soils, but Al-P and Fe-P are more common in acidic soils.

## Organic phosphorus

The amount of organic P in mineral soils can range from 20% to 80% of total P, depending on soil age, organic matter content, climate, vegetation, soil texture, land use, and other factors. The average contribution of organic P to total P varies from 16 percent to 46 percent among states, but intra-state differences in soil organic P are significantly bigger, ranging from 3.2 percent to 73 percent of the total P-content of the soil.

## Measuring soil available phosphorus

As standard assessments of accessible soil phosphorus, more than 10 distinct soil tests are utilized. These standard tests usually include extracting soils with solutions that lower the soil-solution ratio, modify the pH, or introduce anions that displace phosphate ions from soil surfaces. The outcome is phosphorus measurement in the soil solution and from pools that were somewhat loosely adsorbed to the soil, with such procedures referred to as phosphorus amount assays. Standard analytical procedures are then used to determine the concentration of inorganic reactive phosphorus in the extracting. Recently, there has been an increase in interest in the employment of sink approaches, some of which were created quite some time ago, such as resin strip or diffusive gradients in thin films (DGT). These are said to better portray the activity of a plant root than simple solution extraction techniques because they take phosphorus from the soil solution, boosting their supply of soil solution phosphorus and better reflecting genuine phosphorus availability.

**Critical-phosphorus tests:** The available phosphorus identified by soil extraction is compared to predefined target index values to determine whether a soil should receive phosphorus fertilizer treatments. In the United Kingdom, the most commonly used measure of available phosphorus is an Olsen (1954) (sodium bicarbonate) extraction, and current target phosphorus values are generally recommended as 16– 25 mg $L–1 P in soil at or below these values, phosphorus applications that maintain or raise soil available phosphorus concentrations to levels that are assumed to be optimal for plant growth are advised. These target values are drawn on past critical-phosphorus testing rather than soil and crop specifics. Crop output is assessed in a single soil at increasing soil phosphorus concentrations in these studies, with barley grain biomass produced in a low-phosphorus, organic soil as one example. A critical-phosphorus curve's yield grows with phosphorus additions but finally plateaus when phosphorus is no longer the yield-limiting component.

## Phosphorus in agriculture

The introduction of commercial, inorganic, phosphate fertilizers has corrected the inadequate availability of phosphorus in soils over the last 50 years. Phosphate fertilizers are made by collecting phosphate from rocks rich in phosphate minerals and transforming it into a form that is more readily accessible to plants. The use of relatively significant amounts of these fertilizers to agricultural soils over many decades has resulted in phosphorus buildup in many soils. Crops no longer react to extra phosphate fertilizer on those soils. This is currently true for at least half of Tennessee's agricultural soils. Soils with high phosphorus reserves typically do not have a detrimental impact on crop yields, with the exception of reducing the availability of some micronutrients such as zinc. The practice of using phosphate fertilizers to increase soil phosphorus stores was immediately advocated. More oxygen is required for increased development. Growth will continue until either oxygen or phosphorus run out. If oxygen levels fall, all oxygen-requiring or aerobic species in the environment will suffer. If the rate of mortality increases, there will be an increased need for oxygen for decomposition, which will eventually become limiting. When this occurs, the system transitions from an oxygen-based to a non-oxygen-based or anaerobic state. Phosphorus, like in unfertilized soils, is frequently the limiting nutrient in aquatic systems. Aquatic systems, unlike soils, have a poor buffering capacity or ability to hold phosphorus when it exceeds natural background levels. If phosphorus is added to a limited source of water, algae and other aquatic microorganisms will bloom, turning the water greenish and restricting light penetration below the water's surface. With time, oxygen levels will drop to dangerously low levels, and some fish and other aquatic organisms will be replaced by less desirable species. Because of dissolved oxygen depletion in eutrophic waterways, several dissolved constituents (e.g., ammonia, hydrogen sulphate, methane) become potentially harmful to wildlife and cattle.

## How much phosphorus fertilizer dose crops requires

The estimate of the amount necessary to be given to soils for maximum plant development is one of the most significant variables in guaranteeing phosphorus fertilizer usage efficiency. The typical method for calculating how much phosphorus should be supplied is a two-stage approach. First, the soil's available phosphorus status is determined. It is possible to provide recommendations on the amount of phosphorus that should be applied to the soil for specific crops. There are several potential issues with this procedure, not the least of which is that the varying adsorption characteristics of different soil types are rarely taken into account, though some systems do, such as the recommendations of Scotland's Rural College for controlling soil phosphorus. Furthermore, the method of measuring available phosphorus is frequently imprecise and unsuitable for the soil type, i.e., whether the soil is acidic or alkaline.

## Phosphorus in water

Phosphorus, like in unfertilized soils, is frequently the limiting nutrient in aquatic systems. Aquatic systems, unlike soils, have a poor buffering capacity or ability to hold phosphorus when it exceeds natural background levels. If phosphorus is added to a limited source of water, algae and other aquatic microorganisms will bloom, turning the water greenish and restricting light penetration below the water's surface. With time, oxygen levels will drop to dangerously low levels, and some fish and other aquatic organisms will be replaced by less desirable species. Because of dissolved oxygen depletion in eutrophic waterways, several dissolved constituents (e.g., ammonia, hydrogen sulphate, methane) become potentially harmful to wildlife and cattle.

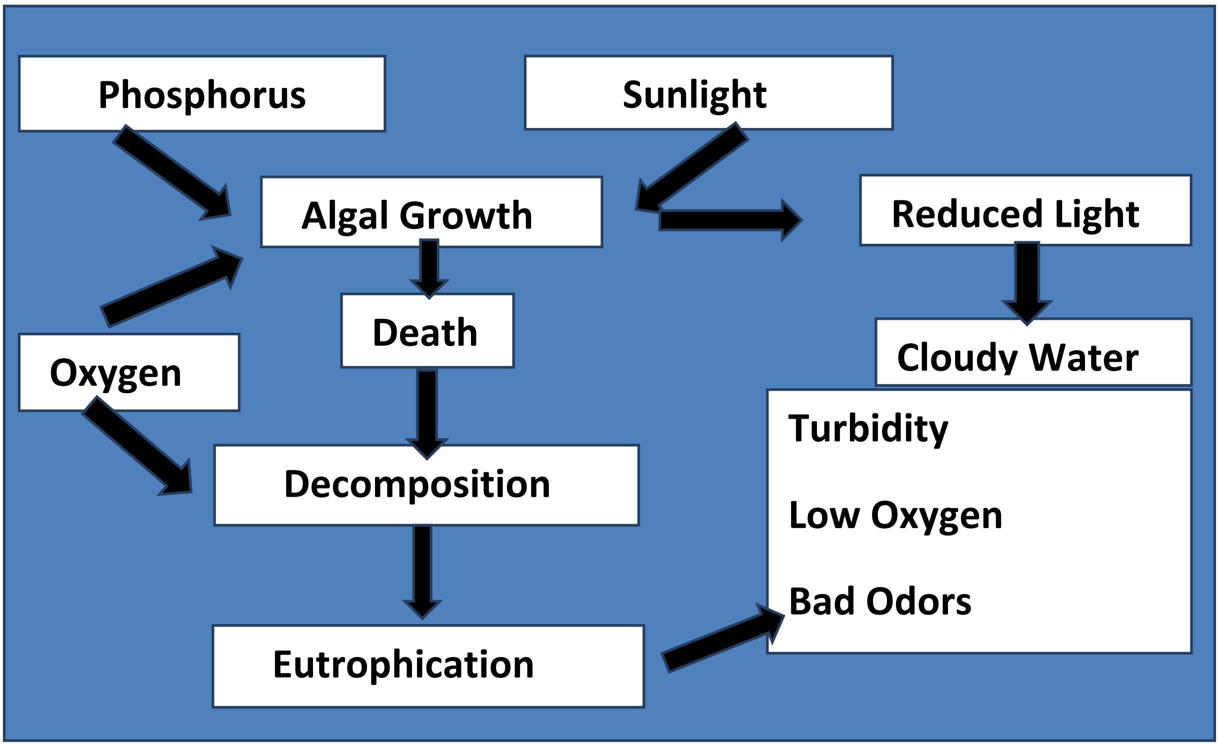

**Figure 1. Effect of phosphorus on Eutrophication**

## Phosphorus Transformation, chemistry and mobilization in soil

**Soil phosphorus pool:** Inorganic P is more likely to be held by soil components with a bond-less accessible for absorption by plant roots, and vice versa. Furthermore, depending on the nature of its physical interaction with holding components in the soil, absorbed P has different extractability or availability. P is classified into four pools based on root accessibility and extractability, and consequently availability to plants. P is instantly accessible for absorption by the plant in this soil solution (first pool). The second pool, which is thought to be in balance with soil solution P, is the readily-extractable P retained on the soil surface faces. The third pool contains less readily extracted P that is more tightly bound to soil components or is present within soil component matrices as absorbed P. With time, this plant may become accessible. The P in the fourth pool has very low extractability and very slow available because of one or more of the following reasons: (1) bonding very strongly with soil component; (2) precipitation as partially-soluble P component; (3) P becoming a part of soil mineral complex; or (4) unavailability owing to its position within the soil matrix. The P in the second and third pools is considered labile, whereas P in the fourth pool is non-liable.

## Chemistry of phosphorus

**Acid soil:** In acidic soil, Al and Fe regulate P solubility. Al $(OH)_3$ is the most soluble of the sparingly soluble Al salts and is the source of Al in acid soil. Because the product of (H+) and (OH-) is constant, when pH drops, H+ ion activity increases while $(OH)^-$ activity declines (ionic product of water). To keep Al $(OH)_3$ constant, the concentration of $Al^{+3}$ ions in solution increases as pH lowers. $Al^{+3}$ ions are in equilibrium with $AlPO_4$. While a result, as the $Al^{+3}$ ion activity increases, the $PO4^{-3}$ ion activity decreases by generating precipitate ($AlPO_4$) to maintain the AlPO4 constant. As a result of the decrease in soil pH, P availability will decrease while P fixation will rise.

Availability of Phosphorus more at the pH of 6-7 and at this pH only P fixation will be very less.

**Alkaline or Neutral soils:** In this situation, calcium ion regulates phosphate solubility. Among the calcium phosphate compounds that are sparingly soluble, di-calcium phosphate (CaHPO4) is the most soluble and will be discussed here-

**Non calcareous soil:** We assume a constant concentration of 10-2.5 moles/L in non-calcareous soil. Because calcium activity is constant, precipitation is determined by the activity of the $HPO4^{-2}$ ion. With rising PH, $HPO4^{-2}$ ion concentration rises, and when it surpasses its solubility product with calcium ion activity, P precipitates out, resulting in a drop in solution P concentration.

**Calcareous soil:** Calcium ion activity in calcareous soil is not continuous but declines with increasing pH since $CO_3^{-2}$ activity increases with PH and when solubility products surpass, it forms precipitate as $CaCO_3$. As calcium ion activity decreases, phosphate ion activity rises to maintain calcium phosphate solubility product constant. As a result, P fixation diminishes as the PH of the calcareous soil rises.

Order of P fixation is Montmorillonite > Vermiculite > Kaolinite > Muscovite

## How much soil phosphorus can potentially be mobilized?

The quantity of P that different techniques may mobilize is determined by the abundance and liability of the desired chemical P species in each soil environment. We examined soil 31P–NMR data from the scientific literature (258 distinct soils from 41 publications) to determine the quantitative speciation of orthophosphate, phosphate monoesters, and phosphate di-esters groups. The NMR approach is typically used with soil NaOH-EDTA extracts to study the chemical structure of alkali soluble P species, which account for approximately 55% of total soil P. This is a harsh extraction method that does not accurately reflect bioavailable P in soils. The decision to employ 31P–NMR data in this research over other approaches was made to evaluate stocks of various P chemical species and their possible future sustainable usage. These concentrations were scaled up into total P stocks (kgPha$^{-1}$) in the first 15cm depth of soil to evaluate the agronomic value of the soil P. The orthophosphate pool accounted for roughly 57 per cent of the NaOH EDTA extractable total P across all samples, whereas the monoester P pool accounted for approximately 33 percent.

## Improving phosphorus use efficiency: what are the problems?

Phosphate cycling in soils is exceedingly complicated, governed by a number of physical, chemical, and biological variables. As a result, determining the amount of phosphate fertilizer necessary for maximum crop development in different types of soils is difficult. It is believed that no more than 8% of phosphorus applied to soil in fertilizers is retrieved in crops, depending on soil type, current physical state, and chemical status. The remaining is either adsorbed to soil particles and organic matter to varying degrees, taken up by soil bacteria, organically completed, or lost to surface waters. Historically, farmers used a preventive approach to phosphorus fertilizer usage, which included over-application, to assure maximum harvests. As a result, phosphorus has accumulated in soils in forms that are commonly referred to as intensity tests. Whatever form of test is employed, the link between the value measured at the start of a crop cycle (or growing season) and plant growth response is ultimately vital, and the better that relationship, the more valuable the soil test. The phosphate buffer index (PBI) or capacity (PBC) of a soil is another crucial indicator for calculating phosphorus availability and how much fertilizer should be supplied. This is a measure of how easily phosphorus associated with the solid soil fraction may become soluble, or of a soil's ability to lock up additional phosphorus, rendering it inaccessible for plant absorption. To reach goal accessible phosphorus indices, soils having a high PBI often necessitate high phosphorus fertilizer application rates. Which means that the existing phosphorus use in the food production and consumption system is unsustainable?

## Environment issue

Phosphorus usage has a direct and indirect environmental impact due to the use of resources (such as water, electricity, and phosphate rock), mismanagement, and the development of waste in huge quantities or with high toxicity, which can pollute receiving areas and harm ecosystems. The literature on the environmental impact of phosphate tends to focus on one element in particular, such as localized consequences during phosphate rock mining and processing (such as water pollution) or the unique biological impact of phosphorus leakage from agricultural soils to aquatic habitats. Phosphorus, on the other hand, has environmental consequences that stretch from mine to field to fork. These effects are felt on a variety of scales and in a variety of sectors:

The stage in the food production and consumption system- mine, to field, to fork to receiving environment;

- **A spatial scale-** global, regional, national, local impacts;
- **A temporal scale-** short, medium or long-term;
- **The responsible parties-** global society, local community, mining/fertilizer/food industry, farmers, retailers, water/sanitation service providers, urban planners, government.

## Impact during fertilizer application and use in agriculture

The environmental implications of fertilizers, from the time they arrive at the farm gate through the effects of application and use. Fertilizers are used on a large amount of the world's agricultural soils. Phosphate rocks are the most common source of phosphorus in fertilizer used across the world; however, other sources like as manure (and to a lesser extent green wastes, other organic wastes, and excreta) are also commonly employed. Indeed, manure is thought to be the primary source of phosphorus utilized in agriculture. (Belgium's Soil Service, 2005) However, the generation of these manures is supported to a large part by feedstuffs produced outside of Europe utilizing mineral fertilizer phosphorus. The environmental consequence of eutrophication can occur regardless of phosphorus supply, although other impacts (such as the presence of cadmium) are more reliant on phosphorus source.

- The effect of phosphorus loss or leaching from farms on aquatic ecosystem functioning and biodiversity is arguably the most significant environmental consequence of phosphorus usage in agriculture. Although phosphorus is not as mobile as nitrogen, it can leak from the field by wind or water erosion (adsorbed to soil particles or organic matter) and a lesser percentage can be carried in solution in soil water (via leaching to ground water or overland flow) (run-off). Phosphorus is derived from either applied fertilizer or manure that has not been absorbed by plant roots or from natural soil phosphorus. Because phosphorus is frequently the limiting component in inland and estuary waterways, excess phosphorus can cause algal blooms to proliferate, which (a) block sunlight, reducing the dissolved oxygen and resulting in anoxic bottom waters, and (b) following the algae’s death and decomposition, toxic compounds are released which result in substantial fish kills and reduction to regions.
- Some heavy metals, such as cadmium, can be found naturally in phosphate rock. This implies that, unless they are eliminated, the use of phosphate rock-based fertilizer can lead to the spread of harmful chemicals in soils.

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