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PHOSPHORUS AS A BOTTLENECK FOR A SUSTAINABLE FOOD SUPLY*

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Summary: *Phosphorus is an essential nutrient for all forms of life, which means that food cannot be produced without it. As the phosphate rock (concentrated source of phosphorus) is a non-renewable and finite resource, with no substitute, without more sustainable management of phosphorus its deposits could be depleted in a rather short period. In addition, much of phosphorus eventually ends up in environment, where it causes pollution. Hence, one could say that the lack of phosphorus and its inappropriate management could be a bottleneck for a sustainable food supply and agricultural development in general. Nevertheless, unlike some other challenges that modern agriculture has to face (for example, water and energy scarcity, climate changes etc) the problem of phosphorus limited availability and accessibility has been largely neglected until recently. This paper's particular intention is to explain why phosphorus management is one of key issues for the sustainable food supply and agricultural development, which factors have to be considered when dealing with this topic and which technologies could be applied as potential solutions. One solution to become independent from the fossil deposits of phosphorus might be its extraction from wastewater, which could contribute significantly to overcome the looming phosphorus and growing environmental crisis.*

Key words: *phosphorus, sustainable agriculture, wastewater*

INTRODUCTION

For any society, a reliable and adequate food supply has always been of high priority. Since the industrial revolution and the connected population growth the productivity of the agricultural sector gained more and more importance. Farmers achieved a major increase in productivity in the agricultural sector during the so called “green revolution”, which started in the United States in the 1950s and spread swiftly to other countries worldwide. The expression “green revolution” describes an industrialization process of the agricultural sector, leading to a tremendous increase of yields, which consequently resulted in the production of vast amounts of food, but with the significant negative environmental consequences. Farmers achieved these yields by introducing new crop varieties and by the excessive application of artificial fertilizers, pesticides and irrigation. Ultimately, except for the first one, all these measures have been driven by the availability of fossil fuels (Cordell et al., 2009).

As a result of the “green revolution” prices for commodities dropped and consumers have benefited from this fact until today. Moreover, the “green revolution” created an attitude that production factors in particular the nutrients in fertilizers are available in limitless amounts (Popp et al., 2012). This was also true for phosphate rock, which was perceived as an inexhaustible source of concentrated phosphorus, a key resource for sustaining the high productivity of today's agriculture (Cordell et al., 2009). However, this attitude changed during the food crisis in 2008, when prices for phosphate rock ballooned by 800% within 18 months. Although the situation has eased in recent times, prices for phosphate rock are still at an elevated level (Neset & Cordell, 2012).

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One solution to become independent from the fossil deposits of phosphor could be its extraction from wastewater. So far the importance of nutrient recovery from wastewater has been underestimated, but it is clear that it could significantly contribute to overcome the looming phosphor crisis (Larsen et al., 2007).

DEMOGRAPHIC DRIVERS OF PHOSPHORUS CONSUMPTION

To understand why an affordable phosphor supply will become crucial in the future one has to analyze the demographic development of the world's population first.

The world population increased significantly from 3 billion in 1960 (UN, 2012) to 7.3 billion in 2015 (UN, 2015). According to United Nations' estimates this trend will continue, resulting in an increase of the word population of 9.7 billion in 2050 and 11.2 billion in 2100 (all values are medium variants) (UN, 2015). However, this growth is not distributed evenly. As figure 1 and figure 2 show there are major differences between developed and less developed countries as well as between urban and rural populations.

Reasons for the significant higher increase of the population in the less developed countries are the improved availability of healthcare and an ameliorated nutrition leading to a decrease of infant mortality and higher life expectancy.

Figure 2 shows another major ongoing trend, namely that since 2010 more people live in cities than in the countryside. As figure 2 indicates, it is expected that in 2050 already more than 6 billion people will live in cities - twice the amount of the rural population. Consequently, there will be more and bigger cities on the planet, which is confirmed by United Nations' statistics.

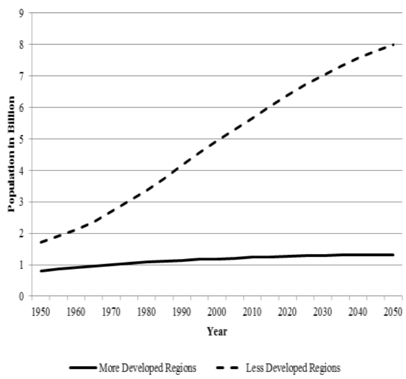


Figure 1. Actual and Estimated Word Population 1950-2050 by Developed/Less Developed Regions (UN, 2012)

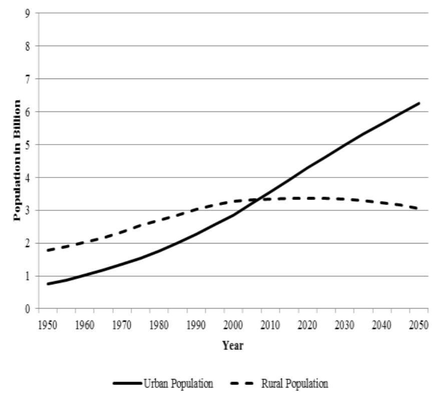


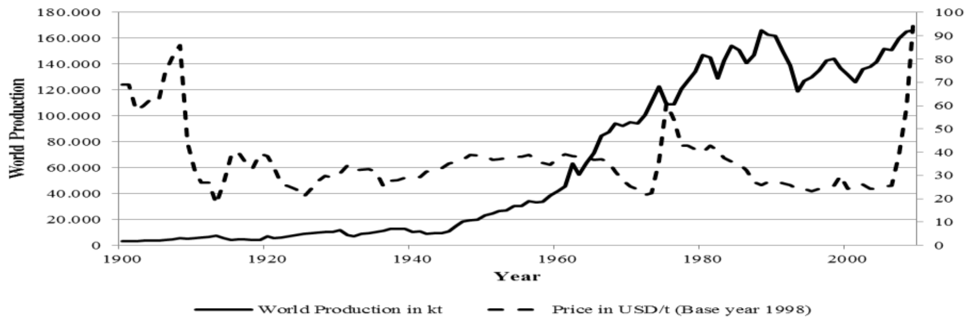
Figure 2. Actual and Estimated Word Population 1950-2050 by Urban/Rural Population (UN, 2012)

Such a situation will have two major consequences. First of all, a growing population means also higher land consumption for housing, industry and road building. Additionally, it results in higher pollution pressure to the available arable land. Natural factors like desertification or salinization put additional stress on arable land worldwide, leading to its diminishment (Pfeifer 2004). Therefore, the arable land per capita will drop significantly, meaning that less land has to feed more people. On the other hand, the fact that people will live more concentrated in metropolitan areas will make the collection, reuse and recycling of material flows, such as phosphor containing wastewater, easier and cheaper.

PHOSPHOR DEPOSITS AND APPLICATION

Beside the carbon, the nitrogen and the water cycle, the phosphor cycle is a key cycle on our planet (Harris, 2005). Nitrogen, potassium and phosphor are the three major fertilizer elements. Farmers apply these elements mostly in the form of compound fertilizers, the so called NPK fertilizers, which are inexpensively available (Déry & Anderson, 2007; Cordell et al., 2009; Lüthi et al., 2011). Phosphor, however, can neither be produced in a virtually unlimited manner like nitrogen (Haber–Bosch process) nor it is as abundant as potassium (mostly in the form of potash). Thus, phosphor represents a limiting factor for natural ecosystems and for agricultural production. Some scholars even attach the same importance to it like to water and energy resources (Déry & Anderson, 2007).

Phosphor is an indispensable basic element for all forms of animal and plant life (Neset & Cordell, 2012). Its



application in the agricultural sector is one of the major reasons for the increase of productivity in arable farming during the last century. Therefore, it is just to say that phosphor feeds the world's constantly growing population by keeping yields at a high level (Cordell, 2009). The mentioned facts make clear that a reliable food supply is highly dependent on the availability of phosphor. Presently 90% of the global phosphate production is used as fertilizer (Rosmarin, 2004). As figure 3 displays, the production of phosphor and its price reached an all-time high in 2008/2009.

Figure 3. World Production and Price of Phosphate Rock 1900-2009 (Buckingham & Jasinski 2010)

Fortunately, this trend did not continue, and prices have somewhat stabilized, but at a much higher level than they were before 2008 (Figure 4).

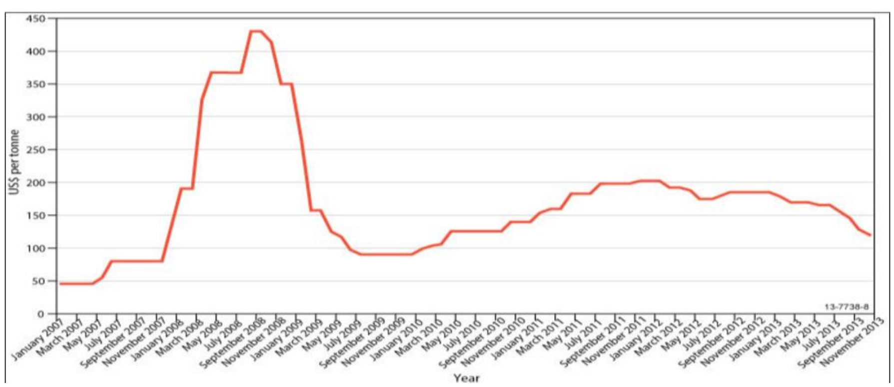


Figure 4. Phosphate rock commodity price 2006-2014 (Word Bank Commodity Price Data)

In 2011 the phosphate rock world production noted at 176.000kt[2], representing an increase of 6%, in comparison to the production in 2009 (U.S. Geological Survey 2011) and the price noted at about 104 EUR/t (World Bank, 2012). The concentration of the world's phosphor producers makes the supply situation even more delicate. As

[2]1kt (kiloton= 10^3 metric tons)

figure 4 shows, the three main producers of phosphate rock; China, the United States and Morocco, cover 67% of the world production.

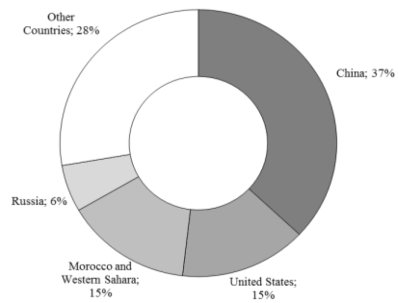


Figure 5. Production of Phosphate Rock 2010 (Buckingham & Jasinski 2010)

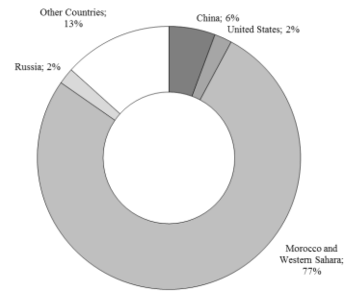


Figure 6. Reserves of Phosphate Rock 2010 (Buckingham & Jasinski 2010)

World reserves of phosphate rock are even more concentrated. As one can observe in figure 5, more than 77% of the reserves are located in Morocco, more precisely in the Western Sahara which Morocco has annexed, flouting an UN resolution. This highly skewed geographical distribution bears the risk of political disputes or even armed conflicts (Rosmarin, 2004; Cordell et al., 2009).

In this context the most pressing question is, for how long the reserves of phosphate rock will last. The U.S. Geological Survey 2011 stated that the world reserves in 2010 accounted for 65.000.000kt. When dividing this figure by the world's production of 176.000kt in 2010 the reserves would last for more than 350 years. Many scholars though, consider this unrealistic. They argue that this calculation neither takes into account the growing world population nor other factors like, for example, the shift to a more meat, dairy, and egg based diet (Sparks, 2011). More importantly, it is also likely, that a significant share of the 65.000.000kt consists of marginal or semi-marginal phosphate rock. This rock consists to less than 26% of phosphorus pentoxide (P_2O_5) and is therefore not marketable - at least today (Buckingham & Jasinski, 2010). So, many scientists consider the realistically exploitable reserves much lower, at 18.000.000kt (Elsner, 2008; Rosmarin, 2004) or even at only 15.000.000kt (Roberson, 2009). Estimations about how long reserves will last, therefore range from 50 years (Déry & Anderson, 2007), 50-100 years (Cordell et al., 2009; Larsen et al., 2007), 115 years (Elsner, 2008) to 130 (Rosmarin, 2004).

As matter of fact, it is nearly impossible to predict accurately the exact point of time, when we will run out of phosphor that is generated from phosphate rock because estimations of the reserves are prone to uncertainty. This uncertainty originates from the high price elasticity of the reserves and the available technological level to exploit them. As more the price of phosphor will increase as more effort will be undertaken to find new deposits of phosphate rock or to exploit known deposits, which were not worthwhile to exploit yet (Hendrix, 2011).

These circumstances, however, do not change the fact that phosphor is a none-renewable resource and its deposits are finite (Neset & Cordell, 2012). Furthermore, issues will not initially commence, when the reserves are depleted but already long before. To these issues belong the soaring price, environmental consequences from mining and the quality of the mined phosphor in terms of heavy metal contamination and radioactive radiation (Larsen et al., 2007; Neset & Cordell, 2012). Therefore, phosphor has the potential to become a bottleneck for agriculture and thereby for our food supply.

TECHNOLOGIES OF PHOSPHOR EXTRACTION FROM WASTEWATER

Wastewater is traditionally perceived as an unwanted product of any society. However, wastewater is a carrier of many valuable nutrients, such as nitrogen and phosphor which may be extracted and re-used. Thus, nowadays sanitation has two major aims, namely to preserve public health by managing the discharge of excreta and to provide nutrients for the agricultural sector (Lüthi et al., 2011). In this context the extraction of phosphor from municipal wastewater is particularly interesting given that one person excretes 1.2 grams of phosphor per day summing up to 3 Mio. t of phosphor per year worldwide (Cordell, 2009).

The centralized end-of-pipe wastewater treatment represents the most common sanitation approach in cities worldwide. In order to avoid eutrophication, most of the modern wastewater treatment plants (WWTP) assure that only 10% of the phosphor, carried by the wastewater, reaches the recipients (Rosmarin, 2004). The remaining 90% are bound in the produced sewage sludge during the wastewater treatment process. The phosphor ions present in the wastewater can be converted into a solid fraction (sewage sludge) either by applying metal ions like calcium, aluminum or iron (chemical phosphor removal) or by incorporating them into cell biomass in the anaerobic conditions (biological phosphor removal)(de-Bashan & Bashan, 2004). Even though enhanced biological phosphor removal results in 96% of phosphor elimination, many authors question its economical feasibility (de-Bashan & Bashan, 2004; Schick et al., 2009). Therefore, today, the chemical phosphor removal is applied more often than the biological phosphor removal.

No matter which kind of phosphor removal process is applied, the final outcome is always a sewage sludge, which is a significant carrier of concentrated phosphor, incorporating ca. 10 g P/kg dry matter (Schick et al., 2009). Phosphor can be recovered from the sewage sludge in two ways. The first option is a direct phosphor recovery from the sludge. Various technologies exist for the direct phosphor elimination, including wet chemical processes (e.g. Seaborne/Gifhorn process), crystallization (e.g. CSH process) and thermal processes (e.g. Mephrec process). The second possibility is an incineration of the sewage sludge. This procedure reduces the total mass of produced sludge and significantly increases the gained phosphor concentration to around 64 g/kg. However, the incineration procedure consumes significant amounts of energy, which makes it expensive.

The NoMix technology, often also referred to as source control or ecological sanitation, is a decentralized wastewater treatment, which was originally considered as a solution for rural and poor regions (Larsen et al., 2009). However, it is also a viable alternative for end of pipe systems or at least a supplement, particularly applicable in new settlement areas, touristic or remote regions. NoMix technology is aiming on the separation of wastewater flows right at the source of origin by evacuating urine (yellow water), faces (brown water) and sullage (grey water) separately. The principal concept is that treating concentrated, unmixed solutions is more efficient than treating highly diluted, combined solutions (Larsen & Gujer, 1997). So, many studies agree that source separation can be resource efficient (Remy & Jekel, 2008).

Urine contains roughly 80% of the nitrogen, 60% of the potassium and 55% of the phosphorus that humans excrete, which make it highly interesting as an alternative to conventional fertilizers (Gensch, 2011). Furthermore, urine is the largest single source of phosphor emerging from cities. Calculations indicate that the urine of the world's population contains 1,68 Mio. t per year of phosphor (Mihelcic et al., 2011).

Three basic technologies exist to collect urine as a separate wastewater flow: vacuum separation toilets, gravity separation toilets and waterless urinals. For any of these installations a separate in-house pipe system and storage facilities have to be set up (Peter-Fröhlich et al., 2008). The collected urine can either be used as a fertilizer directly (after stabilization phase) or it can be collected by trucks and later on be distributed to farmers, who can apply it on their fields. Direct use as a fertilizer is recommended in rural areas, whilst the collection via trucks is more sensible in cities. However, scholars have not yet agreed if urine collection for fertilizing is an efficient solution. For instance Larsen et al. (2009) rejects this idea, whereas Johansson (2000) states that a distance up to 100km would be still feasible. The transport of urine via a separate sewage system to a central collection point does not seem appropriate due to the high investments necessary and the possible clogging of pipes (Lüthi et al., 2011). Furthermore, the direct application of urine is usually undesirable due to its unpleasant odor and the requirement of large storages.

Currently, a combination of end of pipe and NoMix wasewater treatment technologies appears to be the best solution for the phosphorus recovery in growing cities where a sewage system already exists. However, due to the relatively high concentration of phosphor in the urine where only a relatively small amount of matter has to be processed in order to recover the valuable resource it is expected that NoMIX technology will expand in the future.

CONCLUSION

Phosphor is a non-renewable resource with no substitute in agriculture and whose deposits will be most probably significantly decreased or even depleted by the end of the century. Farmers, however suffer already today from extreme volatile and increasing prices of phosphor. The geographical concentration of the world's deposits and the resulting dependency on just a few countries contributes to the uncertainty of phosphor supplies. This unstable situation contributes to the relevance of phosphor recycling. Human excretions, in particular urine, represent a possible substitute for phosphate rock, which is available throughout the world in significant amounts in both, rural and urban areas.

There is no technology of phosphor extraction, which suits best all eventual situations. Decision makers have to carefully analyse the situation at hand and then select the most appropriate technology. Regardless which technology is applied, its implementation is bearing costs. However, due to the assumed price increase of phosphor, its recycling from wastewater could become economically viable sooner than later. Phosphor recycling from within country borders would guarantee a reliable and constant supply. Therefore, recycling would help to avoid price volatility and make the local agricultural sector less vulnerable to extreme price peaks. Consequently, this way of action leads to higher food security.

Beside the economic point of view it is also worth considering the positive side effects of phosphor recycling like water security, less CO_2 emissions and higher hygiene standards due to more advanced sanitation technologies.

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