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Preface

Phosphorus (P) containing waste streams, particularly in the form of manure and wastewater, may hold the key to ensuring an environmentally and economically sustainable supply of P. From such waste streams, struvite ($MgNH_4PO_4.6H_2O$), a regained P fertilizer, can be produced. More and more sewage water treatment plants (SWTPs) and food and agribusinesses in Northwest Europe are starting to recover struvite from their wastewater, mainly since this practice saves them substantial maintenance costs. Finding a good market for this struvite would present a welcome source of added revenues for SWTPs and benefit the circular economy. Because of large surpluses of P from animal manure in the Dutch agricultural sector, there is hardly a market for struvite in the Netherlands however. At the same time, P fertilizers are in great demand among smallholder farmers in Africa, despite the presence of local P reserves. Research further indicates that using a larger share of P fertilizers in African agriculture would be climate smart, as it may allow for more efficient use of fertilizer nitrogen (N), a major contributor to agricultural greenhouse gas emissions. This report aims to assess a possible export of struvite fertilizers from the Netherlands to West Africa in terms of economic potential and greenhouse gas emission reduction. This research was funded by Climate KIC and a part of the Climate KIC Partner Accelerator project P4frica. Climate KIC is a European network aiming to organize transformation of knowledge and ideas into economically viable products or services that help to mitigate climate change. The largest struvite producing water board in the Netherlands, water board Vallei en Veluwe, expressed interest in the idea of exporting struvite to (West) Africa and supported the research with relevant information.

Summary

This report assesses the economic possibilities and greenhouse gas reduction potential of establishing a trade in struvite ($MgNH_4PO_4.6H_2O$), a regained phosphorus (P) fertilizer, between the Netherlands and West Africa. The focus is on (i) verifying economic feasibility and general interest in the idea among buyers and sellers; (ii) verifying greenhouse gas (GHG) emission reduction potential, (iii) reconfirming agricultural and practical feasibility and (iv) inventorying possible legal barriers.

The need to find better markets for struvite becomes evident from agricultural practice. If Dutch farmers, despite the general surplus of P containing animal manure, choose to use mineral P fertilizers, they generally prefer compound soluble fertilizers with a higher N (and K) content than struvite. Hence, there is hardly a market for struvite in the Netherlands. At the same time, smallholder farmers in Africa are in dire need of P fertilizers; research also indicates that African smallholder agriculture could be more climate smart if more P fertilizers would be applied, relative to the current applications of nitrogen (N). Although local P reserves are being mined in several West African countries, virtually none of this P becomes available to local smallholder farmers. Most of it is exported, likely because it generates the greatest profits. Export of relatively low-priced struvite from Europe as a P fertilizer to West Africa could contribute to changing this status quo: it could reduce P surpluses in the Netherlands, improve availability of P fertilizers to smallholder farmers in Africa, make African agriculture more climate smart by improving N use efficiency and enhance the recycling of P, a finite mineral resource.

Similar effectiveness of struvite and mineral P fertilizers under West African conditions was reconfirmed in this study, based on a review of literature on relevant pot and field experiments. Granule size reportedly influences the effectiveness of struvite. In granulated form, struvite behaves as a slow release fertilizer, whereas finely ground, it releases its P much more rapidly. The market value of struvite might hence be improved by turning the product into fine granules. Chemical analyses (Appendix I) further showed that the composition of the struvite from water board Vallei en Veluwe in Apeldoorn slightly differed from pure struvite and that it dissolves better, potentially contributing to a slightly higher market value.

Based on a sales price of about €55,- per tonne of struvite in the Netherlands and on quotes of shipping and handling costs requested from a number of freight forwarders, struvite can be delivered to the ports of Lomé, Dakar or Abidjan at cost prices (raw material + transport and handling costs) between US$ 510,- and 580,- per tonne of P_2O_5.[1] The current world market price of phosphate (P) fertilizers, estimated from the price of DAP (and compensated for N content) is about US$ 640,- tonne of P_2O_5. This seems to confirm economic feasibility, in principle. However, the prices that fertilizer importers and blenders in West Africa are actually paying for P fertilizers may be more relevant than world market prices. Several countries in West Africa, such as Senegal, Togo and Mali, have their own phosphate mines; some of these also produce soluble P fertilizers, almost exclusively for export. Regionally produced P fertilizers might potentially be available below world market prices in these countries. Establishing contacts with fertilizer importers to enquire about prices and verify their interest in importing lower-priced P fertilizers prices proved troublesome and yielded no useful information however.

We estimate the potential greenhouse gas (GHG) emission savings from replacing mineral P fertilizers in West Africa with struvite from the Netherlands at 1.9 - 2.2 tonne CO_2 eq. per tonne of P_2O_5. Given an annual struvite production of ~700 tonnes (175 tonnes of P_2O_5 , Table 1) at SWTP Apeldoorn, this SWTP could realize GHG emission reductions of between ~333 and 382 tonnes of CO_2 eq. per year by

[1] At a rate of 1.0734 US$ per € (March 2017).

enabling use of its struvite as a fertilizer in West Africa. In absence of more specific data, this calculation is based on global average GHG emissions from mineral P fertilizer production of 1.36 tonne CO_2 eq. tonne^{-1} of P_2O_5 . GHG emissions from the production of struvite were negative, mainly because of avoided use of iron chloride (for P removal). Over the longer term, these numbers may subject to change; GHG emission savings may be diminish or disappear. Therefore, use of struvite from Europe in West Africa should mainly be seen as a transitional measure. In the longer run, it is preferable that struvite is produced in sewage water treatment installations in Africa itself and that a local circular economy and local nutrient cycling emerge.

Apart from GHG emission savings, using struvite instead of rock phosphate or mineral P fertilizers also has other environmental advantages. Compared to mineral P fertilizers, its production process consumes much less water and energy and is very clean (there are no waste streams that contain high contents of heavy metals and phosphate). In addition, heavy metal contents in the product are much lower than that of most mineral P fertilizers.

From a review of relevant legal regulations, it was concluded that the export of struvite is most promising if it could be classified as an EC fertiliser; in this case the essential 'End of Waste' status would be easiest to obtain. Both chemically pure and non-pure struvites may classify as EC fertilizers, as long as they contain no organic matter and meet the relevant criteria in terms of nutrient content. This status is yet to be obtained at the time of writing.

An aspect that has remained unclear is the cultural acceptability of using struvite from SWTPs in the Netherlands as a fertilizer in Africa. Depending on local culture, use of human excreta as a fertilizer in Africa may subject to cultural taboos. The best and perhaps only way to find out whether struvite, a clean and odourless product after all, would be acceptable to African farmers is to set up a pilot with the product in farmers' fields in Africa. Such a pilot could include the export process from the Netherlands and import in West Africa and all the required paperwork, hence provide a first indication of practical feasibility. The field experiments would also serve to reconfirm and demonstrate the effectiveness of struvite in comparison with other fertilizers to local farmers. In order to realize such an effort, considerable time and momentum may be required and the participation of a large partner with substantial negotiating and lobbying power, either from the private sector or a NGO, seems a *sine qua non.*

1 Introduction

1.1 Struvite from wastewater

Phosphates play a key role in maintaining food security and overall life on Earth, as phosphorus (P) is an essential nutrient for many biological processes that occur in humans, plants, and animals. Without it, crops would not produce, animals could not survive, and life on Earth would not be possible. As economically accessible mineral phosphate reserves begin to diminish and demand for phosphate is constantly on the rise due to global population growth, scientists worldwide are concerned about food security and the survival of a world without this crucial mineral (Reckinger and Carlson, 2016).

P containing waste streams, particularly in the form of manure and wastewater, may hold the key to ensuring an environmentally and economically sustainable supply of P. From wastewater which contains high concentrations of P and nitrogen (N), struvite ($MgNH_4PO_4.6H_2O$) can be recovered by adding magnesium (Mg) salts under slightly alkaline conditions (Rahman et al., 2016). Major sources of N and P rich wastewater are human food (processing) waste, human excreta, and animal manure. Here, we focus on struvite produced in sewage water treatment plants (SWTPs). More and more SWTPs in Northwest Europe and the Netherlands are starting to recover struvite from their wastewater, mainly since this practice prevents clogging of piping systems hence saves substantial maintenance costs. Making a profit by selling the struvite is not the primary objective. Nevertheless, finding a good market for the struvite that SWTPs produce would generally be a welcome source of added revenues and stimulate the circular economy.

Based on a quick scan of the possibilities for marketing struvite in the Netherlands and Northwest Europe, Timmerman et al. (2016) concluded that, because of the large surpluses of P from animal manure in the Dutch agricultural sector, there is hardly a market for struvite in the Netherlands. NK fertilizers are more in demand and if farmers need P fertilization, they can simply apply animal manure, which contains not only P but also more N and K than struvite and is virtually omnipresent. It is likely that this is also the case in other regions with intensive animal production and manure surpluses in Europe.

At the same time, smallholder farmers in Africa are in dire need of P fertilizers. Research indicates that African smallholder agriculture could be more climate smart if more P fertilizers would be applied, relative to the current applications of nitrogen (N). In Africa, P is often the element that crops need most; it also has a much smaller climate footprint than N. Van der Velde et al. (2013) showed that in Sub-Saharan Africa, the addition of small amounts (10 kg/ha) of N alone resulted in mean maize yield increases of 8% while the addition of only P (10 kg/ha) increased mean yields by 26%. Similarly, based on their study of the effects of long-term N and P fertilization on grain yield and fertilizer recovery in maize in the Great Plains of the USA, Schlegel and Havlin (1995) concluded that apparent fertilizer N recovery in the grain (at 180 kg N/ha) was twice as high with P as without P. Given the relative GHG intensity of P vs. N fertilizer, it would be much more climate-smart to apply more P fertilizer relative to the applied N fertilizer in such cases. Still, in Africa, total N consumption increased by 120% between 1975 and 2005, corresponding with 27,969,103 tons N in 2005. At the same time, total phosphate consumption only increased by 16% to 9,589,102 tons P in 2005 (Van der Velde et al. 2014).

Given the differences in P demand and price between NW Europe and Africa, given the potential for contributing to a more climate smart agriculture in Africa and given the need to establish a global circular economy, an analysis of the possibilities of establishing a trade in struvite fertilizers between the Netherlands and West Africa seems timely; this report summarizes the outcomes of such an exercise.

1.2 Goals of this study

Exporting struvite from Europe to Africa is no common practice yet. Practical, economic and environmental (GHGs) feasibility and cultural acceptability still remain to be confirmed. This study aims to provide an initial inventory of these aspects by:

1. Establishing contact with SWTPs in the Netherlands and inventorying their interest in the concept;
2. Reviewing the suitability, effectiveness and practicalities of using struvite as a fertilizer on African soils;
3. Detailing practical logistic aspects of transporting struvite from SWTP Apeldoorn to a number of major ports in West Africa (Dakar, Abidjan and Lomé). In addition to Apeldoorn, Maastricht was taken as an alternative starting point, to account for maximum possible transport distance to Rotterdam.
4. Verifying economic competitiveness of imported struvite from the Netherlands with other P fertilizers in West Africa, by analysing product prices and transport costs;
5. Verifying the GHG reduction potential use of replacing conventional P fertilizers in West Africa with struvite from the Netherlands, based on GHG emissions from production and transport;
6. If possible, establishing contact with fertilizer blenders in Africa, inventorying their interest to participate and confirm cultural acceptability of the use of struvite as a fertilizer in Africa;
7. Inventorying status and prospects of the relevant regulatory frameworks.

1.3 Methods

Working towards the goals outlined above, the following methods were employed:

1. Contact was established with water board Vallei en Veluwe, currently the water board with the largest struvite producing sewage water treatment plant (SWTP) in the Netherlands, capable of producing 700 tonnes struvite per year. In a joint meeting, they expressed great interest in the current research and agreed to support it with relevant information available. This alone was considered sufficient ground for continuation of the research.
2. Existing research and literature on the application of struvite on African soils was reviewed.
3. Points of origin and destination of the struvite were established and the most practical mode of transport (e.g. big bags on pellets from Apeldoorn to Rotterdam by truck, big bags then to be shipped as break bulk, or in containers) was discussed with freight forwarders and shipping companies. Because of its interest in the project and as it is the largest struvite producing SWTP in the Netherlands, the SWTP of water board Vallei en Veluwe in Apeldoorn was taken as point of origin of the struvite. A number of ports in West Africa (Dakar, Abidjan and Lomé) were selected as potential destinations because of the need for more balanced fertilization / better P fertilization in the hinterland and because of relatively limited shipping distances and hence costs from the Netherlands compared to e.g. Brazil or East Africa.
4. For verifying economic feasibility, product prices of struvite in the Netherlands and prices of conventional P fertilizers in West Africa were reviewed. Shipping and handling costs were estimated by requesting quotations from several freight forwarders, based on the modes of transport defined under 2.
5. GHG emissions data of the production of struvite and mineral P fertilizers were collected from the literature. GHG emissions from transporting struvite from Apeldoorn to West African ports were estimated by combining transport GHG emission factors from the literature with the modes of transport and distances defined under 2.
6. Contact details of fertilizer blenders and importers in West Africa were obtained from directories available at www.africafertilizer.org. Subsequently, it was attempted to interview blenders and importers on their interest in importing an alternative, lower-priced slow-release P fertilizer.
7. To inventory whether the present legal regulations allow for exporting struvite out of the Netherlands and importing it in West African countries, regulatory aspects within the Netherlands and the EU were reviewed and analysed.

2 Suitability of struvite as a fertilizer for West African soils

Yields of important food crops in Africa, such as maize, millet and cassava may be increased by 50 to >100 % (Chianu et al., 2012) by improving the supply of major crop nutrients N, P and K. Similar to N fertilization, increased P fertilization holds large potential for increasing crop yields (Bationo et al., 2012), but in spite of that, the use of P fertilizers remains very low, due to poor availability and high prices. The following section is exploring agronomic suitability of struvite as a potential low-cost, low emissions P fertilizer in West African crop production.

2.1 Pedoclimatic conditions and P status of West African soils

2.1.1 West African soils

Within Western Africa three different pedoclimatic zones may be distinguished: the semi-arid Sahelian zone in the North, south of that the sub-humid Sudanian zone and, even further south, the humid zone. The dominant soils in the Sahelian zone are the Arenosols (according to FAO classification system). These are characterized by sandy texture, low organic matter contents and therefore poor soil structure. The nutrient retention capacity and P availability is low (<2 mg kg^{-1}; Bationo et al., 2007). In the Sudanian zone, Lixisols are dominating. These are characterized by a clay accumulation horizon. Typically, they are only slightly acidic and have a low nutrient retention capacity. Aluminium toxicity is generally not a problem. In the humid zone, highly weathered tropical Acrisols and Ferralsols are dominating. These are strongly acid, provide a very low nutrient retention capacity which frequently leads to deficiency in base cations such as Mg, K and Ca. In Ferralsols Aluminium and Manganese toxicity pose problems as well as P fixation by Al and Fe oxides in Ferralsols as well as Acrisols, limit crop growth (Deckers, 1993). Van Reuler and Prins (1993) concluded for these soils that they are of high physical but low chemical fertility.

2.1.2 West African cropping systems and crop nutrient balances

Main crops cultivated in Western Africa are millet (Sahelian zone), sorghum (Sudanian zone) and maize (Bationo et al., 2007; Buerkert et al., 2001). Low soil fertility, especially low contents of total and available P in soil, is a major constraint to crop production in Sub Saharan Africa (e.g. Gemenet et al., 2016; Bationo et al., 2012; Chianu et al., 2012). In spite of that, the use of P fertilizers is very low due to inaccessibility and high prices. The average P input in African soils is only 1.6 kg P ha^{-1} yr^{-1}, compared with 7.9 in Latin America and 14.9 in Asia (Bationo et al., 2007). Given the resulting nutrient mining and low P status in most West African soils, P status should be restored by applying sufficient P inputs (i.e. greater than the P removed with crop harvests) over a long term (Chianu et al., 2012). Although in some cases, part of the required P input can be supplied by means of organic fertilizers such as animal manures, supplementary application of mineral P fertilizers will often be essential (Chianu et al., 2012). Phosphate rock (PR), which is locally available and much cheaper than regular P fertilizers such as ammonium phosphates and mono calcium phosphates, could be an interesting option for improving the P status of the soil and crop yields at the same time (Chien, 2014). Due to the lower solubility of P in PR (see further), crop available P at the short term is (much) lower than that of regular P fertilizers, but at the long term this difference will become smaller (Bationo et al., 2012). However, mainly due to missing infrastructure and powdery texture, PR has so far not been widely applied (Gemenet et al., 2016). Another interesting low-cost option that has relatively limited attention so far is the application of struvite, which has a lower P solubility than that of regular P fertilizers, such as Single Super Phosphate (SSP; see further) for instance, but higher than that of PR.

2.2 Properties of struvite as P fertilizer in comparison with regular P fertilizers

2.2.1 Phosphate content and solubility

Struvite (magnesium ammonium phosphate) is a relatively new fertilizer, unknown to most fertilizer trading and blending companies and to potential end users (farmers). Mineral P fertilizers are generally characterized by their P content and the contents of other nutrients in the product (Table 1).

Table 1 *Most important P fertilizers with N, P, K, Ca, Mg and S contents, expressed as g N, P_2O_5, K_2O, CaO, MgO and SO_3 per 100 g of fertilizer.*

Product name of P fertilizer	abbr.	P compound	N	P_2O_5	K_2O	CaO	MgO	SO_3
Mono Ammonium Phosphate	MAP	$NH_4H_2PO_4$	12	54	0	0	0	0
Di Ammonium Phosphate	DAP	$(NH_4)_2HPO_4$	18	46	0	0	0.8	3.8
NP 23+23, 26+14, 26+7		Various	23-26	7-23				various
Single Super Phosphate	SSP	$Ca(H_2PO_4)_2.H_2O$ + $CaSO_4$	0	20	0	34	0	31
Triple Super Phosphate	TSP	$Ca(H_2PO_4)_2.H_2O$	0	45	0	24	0	4.5
Ammonium struvite		$MgNH_4PO_4.6H_2O$	5.7	28.9	0	0	16	0
Ammonium struvite WVV			1.8	25	n.d.	0	15	n.d.
Potassium struvite		$MgKPO_4.6H_2O$	0	26.7	17	0	15	0
Soft rock phosphate (Gafsa)		$Ca_3(PO_4)_2$	0	27	0	37	0	0
Rock phosphate (Taïba, Senegal)		-	-	24	-	-	-	-
Rock phosphate (Tilemsi, Mali)		-	-	23-32	-	-	-	-
Rock phosphate (Hahotoé, Togo)		-	-	36	-	-	-	-

The mass fractions of the nutrients of the ammonium struvite given in Table 1 are based on its theoretical molecular composition and the atomic weights of the constituting elements. In reality, the composition of struvite from wastewater treatment plants may slightly deviate from that of pure struvite in terms of dry matter, organic matter and nutrients content. The struvite of water board Vallei & Veluwe (WVV) from the SWTP in Apeldoorn contains 1,8% N, 25% P_2O_5 and 15% MgO; especially its N and P contents are lower than the contents of pure struvite.

In addition to total P content, an indication of crop available P in fertilizers is given by the solubility of P in various extraction solutions (e.g. Kratz et al., 2010; Table 2). This solubility is mainly determined by the P compound(s) and eventual other compounds in the fertilizer. The raw material for the production of most mineral P fertilizers is apatite ($Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{0.4x}(F,OH)_2$), which is present as phosphate rock (PR) in nature. PR may be used directly as fertilizer, but because of its poor P solubility, plant available P is low. By grinding, heating and acidulation of the PR, the solubility of the P can be increased; this principle is applied during the production of mineral P fertilizers. The main P compounds in modern highly soluble P fertilizers are mono calcium phosphate (MCP, e.g. in SSP and TSP) or ammonium phosphate (in MAP and DAP).

Table 2 *Solubility of phosphate (in %) in mono calcium phosphate (MCP), single super phosphate (SSP), di ammonium phosphate (DAP), magnesium ammonium phosphate (= struvite) and rock phosphate (Togo). The amount of P determined with mineral acid is defined as 100%. Sources: Kratz et al. (2010), Bationo et al. (2012).*

Extraction solution	MCP	SSP	DAP	Ammonium struvite	Ammonium struvite (WVV)	Rock phosphate (Togo)
Water	96	76	87	0,73	40	0
Alkali ammonium citrate	95	83	107	6		
Neutral ammonium citrate	97	84	102	92	88	8
2% citric acid	98	88	101	100		
Mineral acid	100	100	100	100	100	100

From Table 2 it becomes clear that struvite is not very soluble in water but much better in neutral ammonium citrate and acids, in contrast to regular P fertilizers based on calcium phosphate (e.g. Mono Calcium Phosphate and Single Super Phosphate) and ammonium phosphate (e.g. Di Ammonium Phosphate). Because of this, it is often concluded that the availability of P from struvite at the short term is lower than that of regular P fertilizers and sometimes it is stated that it could be characterized as a slow release P fertilizer. It may be questioned if that is the case in practice (after application to soils / crops) and if yes, if the efficiency differs from one situation to another (e.g. because of soil characteristics, plant type. etc.).

Chardon (1995) considered the solubility of various P compounds of animal manures and TSP in dependence of pH with a model for chemical equilibria. From these results it becomes clear that the pH dependency differs between P compounds and that TSP has a higher solubility than struvite at pH > 5.5-6, but that the solubility of struvite is higher than that of TSP at pH < 5. So, the statement that the solubility of struvite is lower than that of TSP and similar fertilizers is not true for all situations: it is limited for situations with a pH > 5.5-6.

2.2.2 Dissolution of P fertilizes after application to soil

After the application of P fertilizers to soil, the P dissolves and starts reacting with various soil constituents (Van der Eijk, 1997). Several chemical, physical and biological reactions proceed simultaneously, which finally results in P retention by soil constituents. So, even the application of P fertilizers which are highly soluble in water will in the soil lead to the formation of P compounds that are poorly soluble. This is an important reason for the low P recovery of mineral P fertilizers (in average no more than 10-15% of P applied with fertilizers is taken up by the crop (e.g. Talboys et al., 2016). Important processes taking place in the soil are dissolution, diffusion, sorption and desorption and transport. Generally, the P concentration in the soil solution and the transport distance of P are relatively low, because diffusion is the main transport mechanism.

Because of the complex interactions between soil constituents and P compounds originating from fertilizers, the soil characteristics will affect the effectiveness and availability of P fertilizers. Because of the effect of pH on the solubility of P compounds, pH is an important factor. But also other soil properties, like the P sorption or P buffering capacity of the soil, will affect the P dissolution (Degryse et al., 2016) and probably also the P availability for the crop.

As described earlier, soils in West Africa are poor in P and pH generally varies from slightly to strongly acidic. Struvite is likely to perform better in soils with low pH than in soils with high pH. Degryse et al. (2016) indeed found that dissolution rate of granulated struvite is higher in acidic than in alkaline soil (0.43 mg d^{-1} at pH water 5.9 and 0.03 mg d^{-1} at pH water 8.5). Similarly, Vaneeckhaute et al. (2015) hypothesised that the rhizosphere acidifying effect of the ammonium component of struvite also leads to an increased solubility of struvite. This hypothesis was supported by the observation that in the first three weeks of the greenhouse experiment, the addition of struvite has led to a lower soil pH and a higher P availability than the other fertilizer types. Higher solubility under acidic conditions was also found by Talboys et al. (2016), who observed that initial solubility of struvite was increased at decreasing pH. However, they concluded that the final P concentration at equilibrium (reached after 20-30 days of P application) was independent of pH.

2.2.3 Availability of struvite in comparison with regular P fertilizers

Ultimately, the effectiveness of a P fertilizer is determined by the availability to a crop after its addition to soil. In several studies the crop yield and/or P uptake from struvite by a crop was compared with the yield and/or P uptake from other P fertilizers. As compared to Triple Super Phosphate (which contains mono calcium phosphate) and Di Ammonium Phosphate, struvite resulted in comparable amounts of P taken up by plants in several studies (e.g. Achat et al., 2014 (pH 6.49); Massey et al., 2009 (pH 6.5); Talboys et al., 2016 (pH 6)). As compared to Ca-Phosphates, struvite led to a 12% higher uptake of P (Römer, 2006; soil pH not indicated).

Degryse et al. (2016) argued that in most studies that compare the effectiveness of struvite with that of regular fertilizers, the fertilizers were ground and mixed through the soil. They showed that struvite and the soluble P fertilizer MAP were equally effective in supplying P to wheat when the fertilizers were ground and mixed with soil, but that the MAP was much more effective than struvite when both fertilizers were applied as granules.

Talboys et al. (2016) also conducted experiments with ground and granulated struvite and concluded that granulated struvite behaved as a slow release fertilizer, because it led to a lower P uptake by spring wheat during early growth (first 36 days after sowing). Other studies came up with the conclusion that under slightly acidic conditions (pH 6.49 and pH water 5.4 respectively), struvite solubility was high enough to sufficiently provide P to grass crops (Achat et al., 2014; Bonvin et al., 2015). These different findings could be explained by differences in granule size of the struvite (granules used by Talboys et al and ground struvite used by others) or the fertilizer spreading technique (placement vs broadcast).

2.3 Conclusions and recommendations

Based on the foregoing, the following conclusions may be drawn:

- Struvite P content is lower than that of TSP, MAP and DAP, but somewhat higher than that of SSP. Moreover, struvite contains some N (5%) and MgO (16%), which adds to its value as a fertilizer. The solubility of P in struvite is lower than that of aforementioned 'regular' P fertilizers, but higher than that of PR. For that reason, struvite has good possibilities to be used as a slow release P fertilizer with additional nutrients.
- From pot and field experiments it may be concluded that the crop effectiveness (P recovery) of struvite is similar to regular P fertilizers under most conditions;
- The solubility of struvite is lower than that of most regular P fertilizers, which may lead to a lower P availability during early growth stages of most plants (slow release). This may affect the pattern of P uptake by crops, but often did not result in differences in P uptake and/or yield at final harvest.
- Crop species that exude organic acids in large quantities (e.g. buckwheat), may be able to increase the P availability of struvite also during early growth stages.
- Struvite granule size may affect its dissolution rate after application to the soil: ground struvite dissolves more rapidly than granulated struvite. This may affect P availability during early growth.
- Soil pH affects the initial solubility of struvite, but this is not the case for the final equilibrium P concentration (Talboys et al., 2016). This may explain that soil pH did not affect the effectiveness of struvite.
- Slow release P fertilizers (e.g. struvite and PR) may lead to a lower P recovery at the short term (first growing season), but may contribute to an increase of the P status of the soil and to an improved P supply to crops at the long term (several years).
- The composition of the struvite of WVV Apeldoorn is slightly different from pure struvite and the solubility of the P is higher. This should be taken into account if a comparison with literature data is made.

Given the remaining uncertainties, further research or piloting of struvite application in West African agriculture, and perhaps African agriculture in general, is recommended to (in order of decreasing importance):

- (Re-)confirm the effectiveness of struvite as compared to regular P fertilizers and PR for conditions in West Africa (combinations of crops and soils) in pot and/or field trials.
- Investigate the effect of soil pH on the availability of P from struvite and the optimal soil pH for its application, if P availability and aluminium toxicity are taken into account (Verde and Matusso, 2014). For PR liming to adjust pH to 5.2-5.5 is recommended (Chien, 2014). It should be investigated if this holds similarly true for struvite.
- Investigate whether mixing struvite with soluble P fertilizers, to combine the positive properties of both products (e.g. Talboys et al., 2016) has any advantages for application in practice in West Africa.
- Investigate whether it makes sense to apply a mix of mineral fertilizer with organic amendments (Bationo et al., 2007) to increase the nutrient retention capacity of the soil.

3 Economic feasibility and GHG reduction potential: system definition and boundaries

For assessing economic feasibility and GHG reduction potential of replacing mineral P fertilizers in West Africa with imported struvite from the Netherlands, system boundaries need to be set in a way that allows for comparison, and production and transport scenarios need to be defined.

The assessment in this study is restricted to the **production** of fertilizers (i.e. struvite and mineral P fertilizers) and **subsequent transport** to three *a priori* selected main ports in West Africa: Dakar, Lomé and Abidjan. Costs and emission sources occurring after transferral from port (importer, blender or trader) to wholesalers, retailers and eventually farmers, are disregarded. Expectedly, these costs are similar for struvite and conventional fertilizers, hence this will not skew the comparison.

It needs to be added to this that local transport and distribution often make up a substantial part of the overall end user costs of fertilizers in Africa due to long trip distances, poor roads and poor transportation mechanisms and equipment (e.g. IFDC, 2012; Van Elzakker et al., 2012). Other costs that lead to high fertilizer prices for local farmers, hence may render their use economically unattractive, are finance costs (interest rates applied on input credit) and gross margins for wholesalers and retailers (IFDC, 2012, 2014).

3.1 What mineral P fertilizers could struvite replace?

The P_2O_5 content of struvite is ca. 29% (Table 1), which is in between that of SSP (20%) and TSP (45%), MAP (48-61%) or DAP (46%). Although struvite P is less water-soluble under most conditions, it was concluded in Chapter 2 that it has similar crop effectiveness as aforementioned mineral P fertilizers. Therefore, we assume that struvite could replace these fertilizers on a P_2O_5 equivalent basis. To assess the economic competitiveness of struvite from the Netherlands, we compared its cost price (calculated from product prices in the Netherlands + transport costs, on a P_2O_5 basis) in West Africa with world market prices of DAP (on a P_2O_5 basis). Of the different P fertilizers on the market, price statistics of DAP are most commonly available.

When struvite is applied in the form of granules (instead of a powder), Talboys et al. (2016) found that it behaves more as a slow release fertilizer, in terms of P release. In such case it would perhaps be more appropriate to assume that it could replace phosphate rock (PR). A comparison with world market PR prices was also made therefore.

3.2 Supply chain of mineral P fertilizers

As P is often the nutrient that African crops need most (e.g. Van der Velde et al., 2013), and given the possible economic opportunity for exporting struvite P fertilizer from Europe to West Africa, it is puzzling to note that West Africa itself produces substantial volumes of PR (Table 3) and even soluble P fertilizers. West African countries with substantial phosphate mining activities and/or reserves are Togo, Senegal and Mali (Table 3). However, production is mostly for export (e.g. IFDC, 2014) hence P fertilizers are not becoming available to local (smallholder) farmers. The conclusion that Schreiber and Matlock (1978) drew after inventorying the PR industry in North and West Africa seem still valid today and might be extended to struvite: "phosphate utilization in the region needs to be improved and it may be possible to substitute locally obtained crushed rock (or struvite!) for expensive imported fertilizers. The consequent slower release of phosphate to the soil and eventually to the crops should not be a deterrent in a situation where, in many cases, no phosphate is being applied". Similarly, Adediran and Sobuloby (1998) mentioned PR (discovered at four locations in Nigeria) as a potential source of cheap P to farmers. It is relevant to note here that PR mining demands large amounts of other scarce resources, such as water and energy, and contributes to water, air and soil pollution, greenhouse gas emissions, landscape degradation and solid waste generation (De Ridder et al., 2012). Struvite could perhaps be an affordable, more practical, more effective and more environmentally friendly alternative to PR.

3.2.1 Production of phosphate rock and P fertilizers in Senegal

In Senegal, P mining is carried out by ICS in Taïba (Industries Chimiques Du Senegal). A concentration-drying plant is also located in Taïba. The concentrate is subsequently transported by rail (approx. 110 km) to the Dakar stockyard, from where it is shipped abroad (Van Straaten, 2002). ICS also operates a fertilizer plant (MBAO, 18 km from Dakar) where soluble compound fertilizers such as DAP, SSP, TSP, and complex NPK formulations for export are produced (IFDC, 2014).

Table 3 *World phosphate mine production and reserves in 2014 and 2015 (estimated) in thousands of metric tonnes. Source: USGS (2016).*

Country	Mine production		Reserves
	2014	2015	
United States	25,300	27,600	1,100,000
Algeria	1,500	1,200	2,200,000
Australia	2,600	2,600	1,000,000
Brazil	6,040	6,700	320,000
China	100,000	100,000	3,700,000
Egypt	5,500	5,500	1,200,000
India	1,110	1,100	65,000
Iraq	200	200	430,000
Israel	3,360	3,300	130,000
Jordan	7,140	7,500	1,300,000
Kazakhstan	1,600	1,600	260,000
Mali[a]	N/A	N/A	**12,000**
Mexico	1,700	1,700	30,000
Morocco and W. Sahara	30,000	30,000	50,000,000
Peru	3,800	4,000	820,000
Russia	11,000	12,500	1,300,000
Saudi Arabia	3,000	3,300	960,000
Senegal	**900**	**1,000**	**50,000**
South Africa	2,160	2,200	1,500,000
Syria	1,230	750	1,800,000
Togo	**1,200**	**1,000**	**30,000**
Tunisia	3,780	4,000	100,000
Vietnam	2,700	2,700	30,000
Other countries	2,370	2,600	380,000
World total (rounded)	218,000	223,000	69,012,000

[a] Mali reserve estimate based on Van Kauwenbergh (2010).

3.2.2 Production of phosphate rock and P fertilizers (prospective) in Togo

Togo's phosphate mines are property of SNPT (Société Nouvelle des Phosphates de Togo) and are situated at Hahotoé; ore is transported about 30 km by rail to the harbour of Kpeme, Lomé (van Straaten, 2002; Schreiber and Matlock, 1978) where it is scrubbed, screened, and hydrocycloned to remove clays. The physical processing (beneficiation) of the Togo phosphate ore in Togo results in the recovery of 1 metric tonne of phosphate concentrate per 2 tonnes of raw ore. Hence, the transported weight (from Hahotoé to Kpeme) is double the eventual product (PR) weight. A drawback of the beneficiation is that up to 500,000 tonnes of phosphate fines are discarded annually into the Gulf of Guinea/Benin, which, environmentally speaking, is a cause for concern (Van Straaten, 2002; Boko, 2013). An analysis of the concentration and distribution of major and trace elements in coastal sediments near the dumping site of the phosphate fines in 1998 showed high concentrations of Cd, Cr, Pb, Zn, Cu and Ni in the coastal sediments near the dumping site. The highest Cd enrichment factor of 100 was measured in relatively coarse sediments, close to the dumping site and along the shore, transported by longshore currents. It was also mentioned that Cd is easily mobilized in seawater and thus pollutes much larger areas of the Gulf of Guinea/Benin (Van Straaten, 2002).

Interestingly, Schreiber and Matlock (1978) mentioned plans for developing a complex for the production of fertilizers (from PR) in Togo. Van Straaten (2002) however reported that there was no facility for downstream processing of Togo PR into phosphate fertilizer, and that most of the concentrate was still exported. Only recently, the Israeli Elenilto group has won a bid to build a $1.4bn phosphate mining and fertilisers plant in Togo, which will produce phosphate concentrates, facilitated by West African Gas Pipeline's (WAGP) natural gas pipeline (Chemicals-Technology.com, 2015). The company will also establish a downstream phosphoric acid and fertiliser plant to serve the increasing demand from African and international customers, and distribution channels and logistics facilities to supply fertilisers to the farmers. Sales of concentrates is expected to begin within three years (Chemicals-Technology.com, 2015), which would be in 2018. Also, a fertilizer blending plant (Compagnie des intrants agricoles du Togo) with a capacity of 400,000 tonnes of fertilizers per year was opened in the port of Lomé in June 2015 and is operated by the French Mambo group. Plans for a constructing a similar plant in Abidjan are also reported (Jeune Afrique, 2015).

Figure 1 *Phosphate mining at SNPT in Togo (photo: A. Pugachevsky, https://commons.wikimedia.org/wiki/File:Togo_phosphates_mining.jpg; original image).*

3.2.3 Assumptions made on origin and modes of transport of mineral P fertilizers

Based on the above, we assume in our comparison that the soluble mineral P fertilizers that could be replaced with struvite are produced in West Africa itself. Although locally produced P fertilizers (and P fertilizers in general) are often unavailable to local farmers, regional use would in principle be the most desirable situation; it entails minimum transport emissions and implies that the natural resources of the region are utilized by the people of the region which may be pro-poor. Also, West African countries with domestic P mining activities presently import little to no P fertilizers[2]. Thus, we made our analysis based on transport distances from fertilizer plant to port (Sections 3.2.1. and 3.2.2) of 110 km (Dakar), 30 km (Togo) and 585 km (Abidjan, by road from Lomé, Togo), with the remark that the aforementioned Elenilto fertilizer plant in Togo is currently not yet in operation. Distances and modes of transport are summarized in Table 4. As no specific emission data for African trucks or trains were available, GHG emission factors (Table 4) were taken from CE (2016b), which may be on the conservative side.

Table 4 *Distances[a] and assumed means of transport for regionally produced P fertilizers from production sites to three West African ports.*

Section	Means of transport	Distance km	EF[a] (g CO_2 eq./tonne km)
SNPT Hahotoé – Kpeme (Lomé)	Diesel train, heavy bulk, long	30	34[b]
SNPT Hahotoé – Abidjan	Diesel train, heavy bulk, long (Hahotoé – Kpeme)	30	34[b]
	Heavy tractor-semitrailer (bulk, Kpeme-Abidjan)	585	102
ICS Taïba – Dakar	Diesel train, heavy bulk, long	18	17

[a] GHG Emission Factor; source: CE (2016b).

[b] The GHG emissions factor for rail transport from Hahotoé to Kpeme (17 g CO_2 eq./tonne km) was multiplied by 2, to account for the fact that 2 tonnes of raw ore are transported per tonne of rock P.

3.3 Supply chain of struvite

The supply chain of struvite considered in our analysis starts with the production of struvite in the Netherlands, at SWTP Apeldoorn, and includes subsequent shipping to the ports of Dakar, Lomé and Abidjan. In the production of struvite at the SWTP, the following steps can be distinguished:

1. Sewage sludge is concentrated and processed in an anaerobic digester.
2. Phosphate is recovered from the anaerobic digester sludge as orthophosphate (PO_4-P) and ammonia nitrogen (NH_4-N) with the NuReSys technology (Nuresys, 2016): a two stage process involving first a stripper reactor and subsequently a crystallizing reactor. The stripper reactor primarily serves to control pH. In the crystallizing reactor, added Mg ions react with the present P and N to form $MgNH_4PO_4.6H_2O$, which then precipitates as pure struvite crystals of 1-3 mm in size (Nuresys, 2016). It should be remarked that in reality, the composition of the obtained product may slightly deviate from that of pure struvite (c.f. section 2.2.1 and Table 1).
3. The crystals are stored in big bags of 1m^3 (Figure 2). Annual production at SWTP Apeldoorn is ca. 700 tonnes; given a specific weight of struvite of 1.7 tonne m^{-3}, this corresponds to 412 m^3 struvite, hence 412 big bags. Based on advice from freight forwarders/shipping companies, these big bags are best shipped in Twenty Foot Equivalent Units (TEU). The maximum loading weight per TEU is 24 tonnes[3]. Subtracting the tare mass of the container itself (2.4 tonnes[1]), the maximum amount of cargo per TEU is reduced to approximately 21,6 tonnes. Hence, a TEU can

[2] Source: www.africafertilizer.org, consulted April 2017.
[3] https://en.wikipedia.org/wiki/Twenty-foot_equivalent_unit.

hold 12 big bags of 1.7 tonnes each (Table 5)[4]. For transferring 412 big bags per year, 35 TEU are required.

Table 5 *Gross, net and tare weights of a TEU loaded with 1m³ big bags of struvite*

Unit	Max. total weight	Tare weight	Max. load	Weight 1 m3 big bag of struvite	Max. big bags per TEU	Net weight	Gross transport weight
	Tonne	Tonne	Tonne	Tonne		Tonne	Tonne
TEU	24	2.4	21.6	1.7	12	20.4	22.8

4. Transport of TEUs loaded with big bags of struvite from the SWTP storage in Apeldoorn to the port of Rotterdam is assumed to take place by heavy tractor + semi-trailer; emission factors for this mode of transport were derived from CE (2016b).
5. From the port of Rotterdam to the ports in West Africa (Dakar, Lomé or Abidjan), transport by ship is preferred to keep costs at a minimum. The weight of a TEU containing 14 big bags is 22,8 ton, including the weight of the container (Table 5). GHG emissions were based on gross TEU weight, emissions factors per tonne km for short sea shipping (CE, 2016b) and the trip distances[5]. Emission factors depend on vessel tonnage; for medium weight container short sea transport, CE (2016b) gives values of 26, 23 and 21 g CO_2 eq. $tonne^{-1}$ km^{-1}) for Handysize-like, Handymax-like and Panamax-like ships (in order of increasing tonnage). Although Lomé is on the list of Panamax ports[6], Dakar and Abidjan are not; also, it seems likely that even in Lomé, smaller ships may be relatively more common than Panamax ships. Therefore, we base our calculations on emissions from Handymax-like vessels (23 g CO_2 eq. $tonne^{-1}$ km^{-1}).

Table 6 *Distances[a] and assumed means of transport for shipping struvite from the SWTP in Apeldoorn to several West African ports.*

Section	Means of transport	Distance	EF[b]
		Km	(g/tonne km)
Apeldoorn-Rotterdam	Heavy tractor-semitrailer (2 TEU)	175	102
Maastricht-Rotterdam	Heavy tractor-semitrailer (2 TEU)	200	102
Rotterdam-Dakar	Handymax vessel, medium load	4,863	23
Rotterdam-Abidjan	Handymax vessel, medium load	7,039	23
Rotterdam-Lomé	Handymax vessel, medium load	7,628	23

[a] Distances over sea based on http://www.marinetraffic.com/en/voyage-planner.

[b] GHG Emission Factor in g CO_2 eq./(tonne * km); source: CE (2016b).

[4] The maximum loading weight of a Forty Foot Equivalent Units (FEU) container is not much larger than that of a 20ft container, namely 26.5 tonnes. As transport costs are much higher, transport by FEU would make no sense.
[5] http://www.marinetraffic.com/en/voyage-planner.
[6] https://en.wikipedia.org/wiki/List_of_Panamax_ports.

Figure 2 *Struvite stored in 1m^3 big bags at SWTP Apeldoorn (photo: S.C. de Vries).*

4 Economic feasibility

Crucial question in exporting struvite to West Africa and marketing it as a P fertilizer there is at what cost price the struvite can supplied to West African ports and what the prices of competing products are.

4.1 At what cost price can struvite from the Netherlands be supplied in West African ports?

The potential cost price of struvite from the Netherlands in West African ports depends on two main factors: the price that needs to be paid to the producers in the Netherlands (i.e. water boards) and the total cost of transport and export to West Africa, including documents etc.

4.1.1 Struvite prices in the Netherlands

STOWA (2016) estimate the market value of struvite in the Netherlands, based on actual fertilizer prices and its content of mineral N, soluble P and magnesium to be about **€55,- per tonne**, when supplied in the form of granules or as a raw material for the production of fertilizers. This was confirmed as realistic by experts from the Dutch water treatment sector (pers. comm., 2016). Therefore, we base our analysis on that price. It needs to be remarked that the quality of struvite (moisture content, colour, organic matter content, etc.) influences its price. Struvite from SWTP Apeldoorn is generally of good quality: clean, dry and odourless, with a sandy texture (Figure 3).

Figure 3 *The struvite from SWTP Apeldoorn is of good quality generally: clean and dry and odourless, with a sandy texture (photo: S.C. de Vries).*

4.1.2 Export/transport costs

Quotes for transport of a TEU loaded with struvite from SWTP Rotterdam and Maastricht to West African ports (Dakar, Lomé, Abidjan) were requested from several freight forwarders and shipping companies. Maastricht was taken as a proxy of the maximum possible distance from Rotterdam in the Netherlands and hence maximum (domestic) transport costs. Based on the obtained quotations and on the gross and net weights of a TEU loaded with big bags of struvite (Table 4), transport costs from

Rotterdam/Maastricht to Dakar/Abidjan/Lomé were estimated per tonne struvite and per tonne P_2O_5, both in Euros and US dollars (Table 7).

Table 7 *Estimated transport costs of a TEU loaded with big bags of struvite, based on quotes from freight forwarders and the net weight of the loaded TEU (Table 4).*

	Dakar	Abidjan	Lomé
Struvite price in Netherlands, per tonne (section 4.1.1)	€ 55.00	€ 55.00	€ 55.00
Transport costs 1 TEU, from Apeldoorn (based on quotes)	€ 1,365.00	€ 1,300.00	€ 1,635.00
Net struvite weight per TEU (tonnes, Table 4)	20.4	20.4	20.4
Transport costs one tonne of struvite, from Apeldoorn	€ 66.91	€ 63.73	€ 80.15
Total costs per tonne of struvite, delivery at port	€ 121.91	€ 118.73	€ 135.15
Total costs per tonne of P_2O_5, (25% content) delivery at port	€ 487.65	€ 474.90	€ 540.59
Total costs per tonne of P_2O_5, delivery at port, US$	**$523.44**	**$509.76**	**$580.27**
Transport costs 1 TEU, from Maastricht (based on quotes)	€ 1,445.00	€ 1,385.00	€ 1,715.00
Net struvite weight per TEU (tonnes, Table 4)	20.4	20.4	20.4
Transport costs per tonne of struvite, from Maastricht	€ 70.83	€ 67.89	€ 84.07
Total costs per tonne of struvite, delivery at port	€ 125.83	€ 122.89	€ 139.07
Total costs per tonne of P_2O_5 (25% content), delivery at port	€ 503.33	€ 491.57	€ 556.27
Total costs per tonne of P_2O_5, delivery at port, US$	**$540.28**	**$527.65**	**$597.11**

4.2 Market prices of products that could be replaced with struvite

4.2.1 Struvite prices compared with the price of DAP, per tonne of P_2O_5

Prices of DAP (18:46:0) on the world market[7] and in Senegal[8] over the past years were used as a proxy for P_2O_5 prices in soluble mineral P fertilizers and compared with the cost prices (from Table 7) of struvite from the Netherlands in West Africa (calculated in section 4.1.2, Table 7). Results are summarized in Figure 4.

It appears that struvite from the Netherlands (Table 7) can generally be supplied to ports in West Africa below world market prices of P_2O_5. The actual P_2O_5 prices that importers, blenders and traders pay remain unclear however. Little to no P fertilizers are imported, generally, particularly in countries with their own P mining activities[8]. It was attempted to gauge the interest in importing struvite of several private companies active in importation and distribution of fertilizers in West Africa, such as ICS and AGROPHYTEX SA in Senegal, WIENCO, Golden Stork and Chemico in Ghana, Toguna Agro Industries in Mali, OLAM in Ghana, Cote d'Ivoire, Togo and Senegal and Afcott in Cote d'Ivoire and Ghana. However, contact details were generally difficult to find or appeared erroneous; in the other cases, no reply was received. This might indicate a general lack of interest in importing P fertilizers. In conclusion, it remains unclear whether imported struvite can be cheaper than regionally produced P fertilizers, as no data of the actual prices of such fertilizers are available. Our estimated struvite prices seems to compare favourably with official DAP prices in Senegal, for instance (Figure 4); however, these are retail prices. If, based on IFDC (2014b), we assume additional inland costs of ~35% on top of the import price to arrive at the retail price, it seems that imported struvite might still be able to compete with DAP in Senegal.

[7] Source: www.indexmundi.com, consulted April 2017.
[8] Source: www.africafertilizer.org, consulted April 2017.

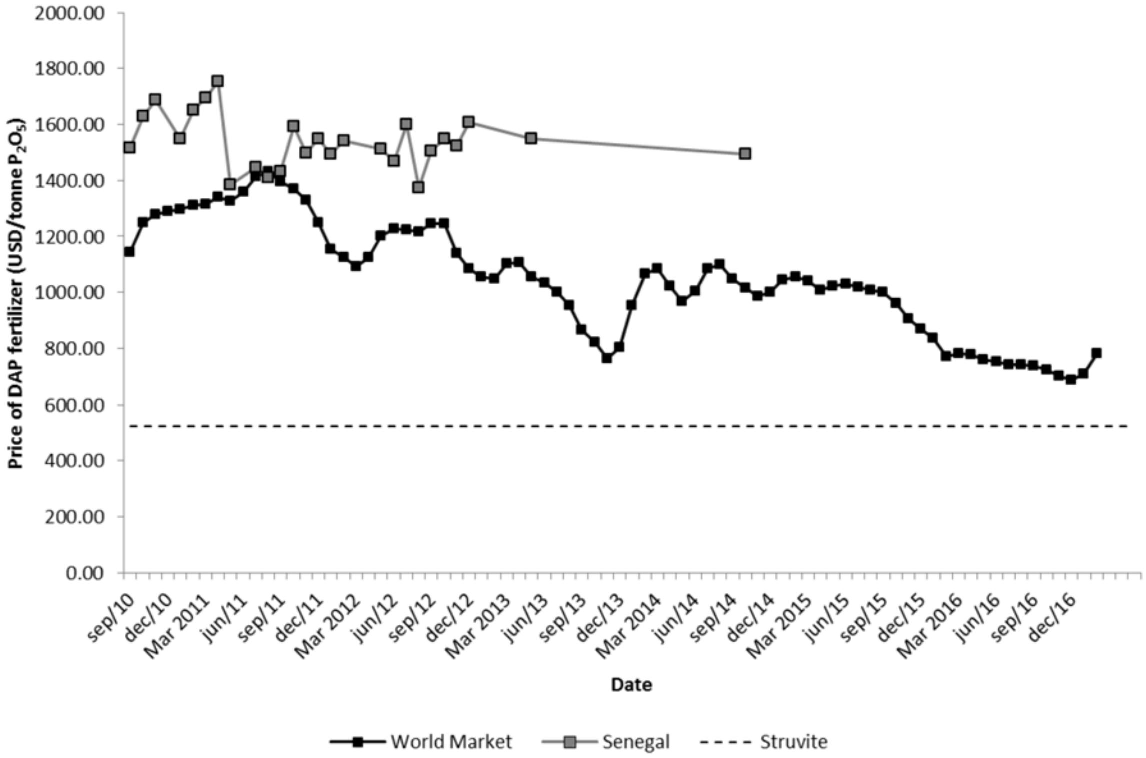

Figure 4 *DAP prices on the world market (source: www.indexmundi.com) and in Senegal (retail; source: www.africafertilizer.org), compared with the estimated cost price of struvite from the Netherlands in Dakar (Table 7).*

4.2.2 Struvite cost prices compared with world market prices of DAP on a P_2O_5 basis and corrected for N content

In afore comparison, DAP prices were used as a proxy for P_2O_5 prices, based on P_2O_5 content (46%) only. However, DAP also contains 18% N, which likely contributes to its market value. Struvite normally only contains ~5.7% N, or, in the case of the struvite from Apeldoorn, only 1.8% (Table 1). To correct for this difference, we discounted DAP prices with 12.3% and 16.2% of the value of its N. The value of N was estimated from world market urea prices (www.indexmundi.com) and N content (46%). This can be summarized in the following formula:

$$P_{DAP,\ corrected} = (Pr_{DAP} - (N_{DAP} - N_{struvite})\ (Pr_{urea} / N_{urea})) / P_2O_{5,\ struvite}$$

Where:

$Pr_{DAP,\ corrected}$	price of DAP, corrected for N content and per tonne of P2O5, to enable direct comparison with the price of struvite;
Pr_{DAP}	market price of DAP, expressed per tonne of DAP;
N_{DAP}	N content of DAP (18%);
$N_{struvite}$	N content of struvite (5.7% in general, 1.8% in struvite from Apeldoorn);
Pr_{urea}	market price of urea;
N_{urea}	N content of urea (46%);
$P_2O_{5,\ struvite}$	P_2O_5 content of DAP (46%)

DAP prices corrected according to Eq. 1 for comparison with struvite containing 5.7% and 1.8% N and are displayed in Figure 5. The cost price at which struvite from the Netherlands (Apeldoorn) could be supplied in the port of Dakar (calculated in section 4.2, Table 6) is also indicated. After correction for N content, it appears that struvite from the Netherlands can still be supplied to West African ports below world market P_2O_5 prices. Again, the prices that importers actually pay remain unknown and whether imported P fertilizers can be cheaper than local products is unclear, as no data of the cost of production and transport of such fertilizers are available.

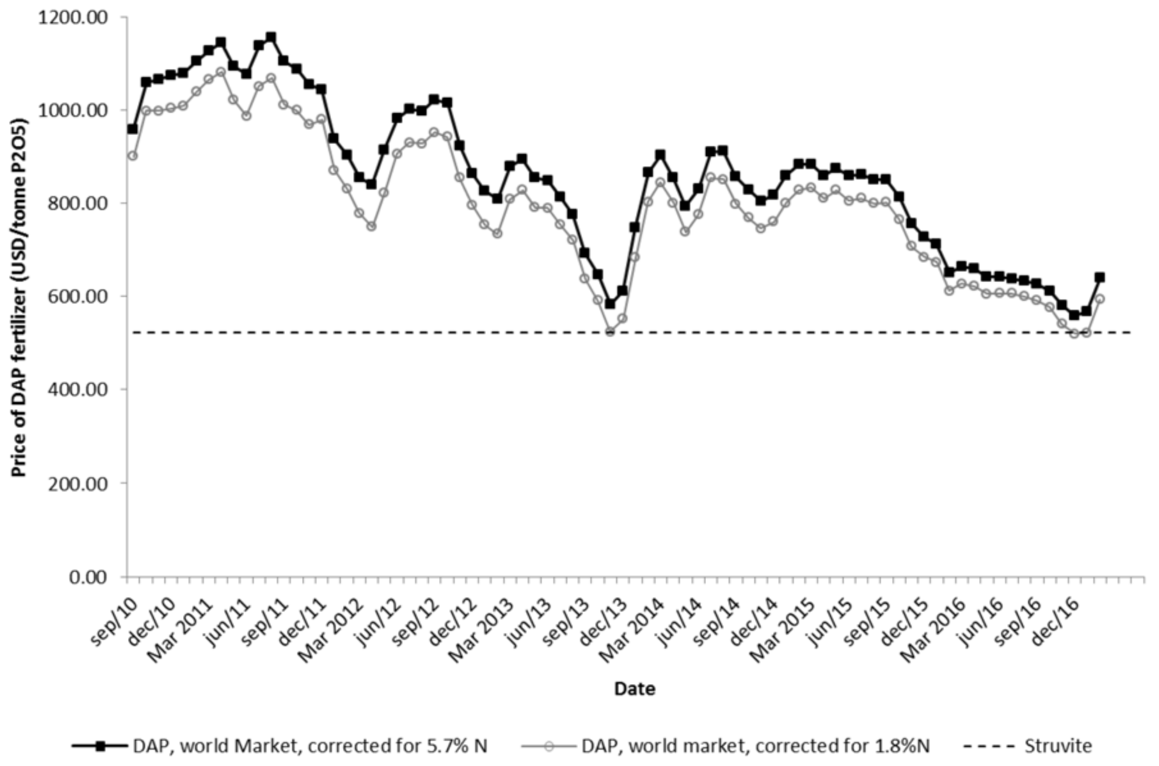

Figure 5 *World market prices of DAP (on P_2O_5 basis), corrected for N content for comparison with struvite containing 5.7% N and 1.8%N (SWTP Apeldoorn), and the estimated cost price of struvite from the Netherlands in Dakar (Table 7).*

4.2.3 Struvite cost prices compared with market prices of rock phosphate, per tonne of P_2O_5

When struvite is applied in the form of granules, its behaviour in the soil may bear more similarity with rock phosphate (PR) than with soluble mineral P fertilizers. A comparison with world market PR prices was made therefore (Figure 6), converting prices per tonne rock P to prices per tonne P_2O_5 assuming an average P_2O_5 content of 35% (EFMA, 2000).
It appears (Figure 6) that struvite from the Netherlands can generally not be supplied to West African ports at cost prices below world market prices of PR. However, the agricultural value of PR may also be lower than that of struvite, and its powdery texture may be impractical for on-farm application and transport. Similar to soluble P fertilizers, the actual prices that importers pay for PR remain unclear. In addition, little to no PR is imported generally, particularly in countries with P mining activities.

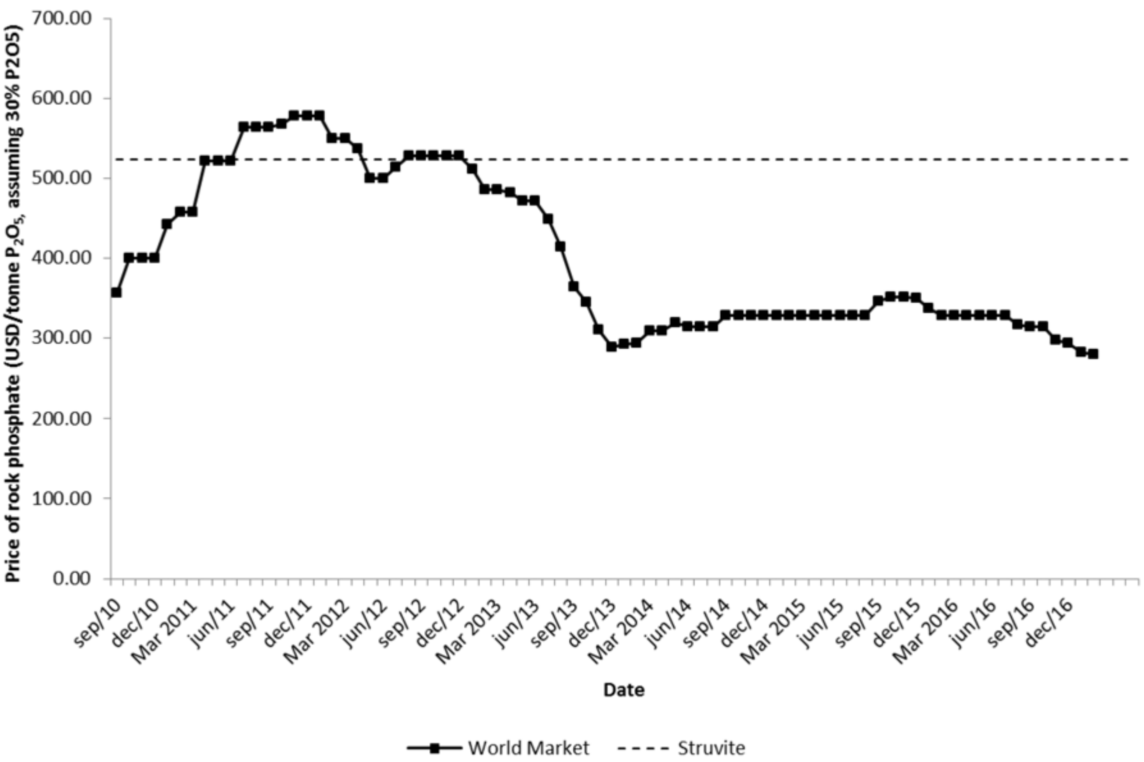

Figure 6 *World market prices of rock phosphate (on P_2O_5 basis, assuming 35% content, based on EFMA, 2000; source: www.indexmundi.com), and the estimated cost price of struvite from the Netherlands in Dakar (Table 7).*

4.3 Conclusion and outlook

Struvite from the Netherlands can be supplied to the West African ports of Dakar, Abidjan and Lomé below world market P_2O_5 based prices of soluble P fertilizers (Table 6; Figures 4 and 5). However, the prices that local fertilizer importers, blenders or traders pay for P fertilizers remain unclear. If, based on IFDC (2014b), we assume additional inland costs of ~35% on top of the import price of fertilizers to arrive at the retail price, it seems that imported struvite might be able to compete with DAP in Senegal. It needs to be remarked that West African countries currently import only small quantities of P fertilizers, particularly those that have their own P mining activities.

Struvite from the Netherlands can generally not be supplied to West African ports below world market P_2O_5 based prices of rock phosphate (PR; Figure 6). Although prices of PR are lower than those of struvite, its agricultural value may be correspondingly lower. There is little to no import of PR in West Africa currently (africafertilizer.org). In addition, local PR from Senegal and Togo (and several other countries in West Africa) is generally not well suited for direct application as a fertilizer due to low reactivity, and it is mostly exported as a raw material. A type of PR from the region that has relatively high reactivity and hence is suitable for direct agricultural application is Tilemsi phosphate from Mali. Based on its relatively high retail price in Mali and the high costs of transport in the region, it seems unlikely that this product can compete with local or imported P fertilizers in the coastal countries of West Africa.

The situation sketched above is not expected to change rapidly. Beer & Co. (2016), for instance, assume a long-run world market price of US$ 115,- per tonne of rock P, which is slightly higher than the current price (US$ 98,- per tonne of rock P, February 2017). Furthermore, Beer & Co. (2016) take US $115/tonne as the lower end of the expected range of future PR prices.

5 Climate benefits

5.1 Greenhouse Gas emissions from production

5.1.1 GHG emissions from the production of conventional P fertilizers

Kool et al. (2012) calculated GHG emissions from the production of SSP, TSP, MAP and DAP fertilizers, based on the relative quantities of PR and phosphoric and/or sulphuric acid required for producing these fertilizers. They also calculated the average carbon footprint of P-fertilizer use for a number of regions of the world and for the world as a whole, based on the relative shares of the different types of P fertilizers used in agriculture (e.g. SSP, TSP, etc.), and the GHG emissions from their production. However, in these calculations, no African data were taken into account, hence the global average GHG emissions of P fertilizer use of **1.36 kg CO_2 eq. kg^{-1} of P_2O_5** that they arrived at does not extend to Africa, in principle. However, in absence of better data, we used this figure as the benchmark carbon footprint from the production of 'conventional' P fertilizers.

5.1.2 GHG emissions from the production of struvite P fertilizers

Struvite is produced by adding Mg ions to phosphate containing wastewater at slightly alkaline conditions, resulting in the precipitation of insoluble $NH_4MgPO_4{\cdot}6H_2O$ crystals. GHG impact from the production of struvite was estimated based on CE (2016a), who provide estimates for struvite production from wastewater in the Dutch potato processing industry. Although struvite production requires some electricity (CE, 2016a), this requirement may be more than compensated for by biogas production in the SWTP. Instead of crediting any surplus energy generation to the production of struvite, we assumed that the process is energy neutral. We did not credit struvite with the fertilizer replacement value of the N and P that it contains either, as our very aim is to investigate the potential GHG benefits of such a replacement. Hence, our estimate of the GHG emissions from struvite production is only determined by its MgO requirement (0.20 kg CO_2-eq./kg struvite), by the fact that iron chloride, normally used to remove phosphates (Meulenkamp and Buunder-Van Bergen, 2016), is no longer needed (-0.59 kg CO_2-eq./kg struvite), and by emissions from the combustion of sludge (0.04 kg CO_2-eq./kg struvite). These three terms together result in a net GHG emission reduction of **-0.35 kg CO_2 eq. kg^{-1} of struvite** (i.e. a reduction in GHG emissions compared with the normal practice). At a P_2O_5 content of 25% (Table 1, WVV/SWTP Apeldoorn), this is equivalent to **-1.40 kg CO_2 eq. kg^{-1} of P_2O_5.**

5.2 Greenhouse Gas emissions from transport

5.2.1 GHG emissions from transport of struvite and conventional P fertilizers

Struvite. Transport of struvite from the SWTP in Apeldoorn to selected ports in West Africa is assumed as outlined in section 3.3; road transport from SWTP Apeldoorn or Maastricht to the main port of Rotterdam, from there by ship to West Africa. Means of transport, distances and GHG emission factors CE (2016) were summarized in Table 6.

P fertilizers. Transport of P fertilizers produced in Senegal and Togo to the ports of Dakar, Lomé and Abidjan is assumed to take place as outlined in section 3.2. In Senegal, P concentrate is transported by rail from Taïba to Dakar; in Togo, the raw ore is transported by rail from Hahotoé to Kpeme/Lomé. Transport of regionally produced P fertilizers to Abidjan in Cote d'Ivoire, a country that does not have phosphate mining activities, is assumed to occur by road from nearby Togo (Kpeme). Means of transport and distances were summarized in Table 4.

5.2.2 Total emissions from the production and transport of conventional P fertilizers

Total emissions from production of P fertilizers in the region and transport to the ports of Dakar, Lomé and Abidjan, calculated based on data in Table 4 and GHG emissions from P fertilizer production of 1.36 kg CO_2 eq. kg^{-1} of P_2O_5 (Kool et al., 2012) are summarized in Table 8. Production (including mining) of P fertilizers causes by far the largest share of the GHG emissions; transport makes a relatively modest contribution. Further, transport by truck and semi-trailer from Lomé to Abidjan causes larger emissions than rail transport as it involves a large distance and has a relatively high emission factor.

Table 8 *Estimated GHG emissions from production of P fertilizers in Senegal and Togo and subsequent transport to the ports of Dakar, Lomé and Abidjan.*

Section	Transport mode	Distance Km	WTW GHG Emission Factor (a) g CO_2 eq. $t^{-1}km^{-1}$	WTW GHG emissions transport, 1 tonne of PR, section kg CO_2 eq.	WTW GHG emissions transport, 1 tonne of P_2O_5, section kg CO_2 eq.	Total WTW GHG emissions transport 1 tonne of P_2O_5, total kg CO_2 eq.	Total GHG emissions, transport + production, 1 tonne of P_2O_5 kg CO_2 eq.
Production of P fertilizers	-	-	-	-	**1360 (c)**	-	-
SNPT Hahotoé – Kpeme (Lomé)	Diesel train, heavy bulk, long	30	17	1.02 (b)	3.11 (d)	3.11	**1363.11**
SNPT Hahotoé – Abidjan (Ivory Coast)	Diesel train, heavy bulk, long	30	17	1.02 (b)	3.11 (d)	-	-
	Tractor-semitrailer (heavy bulk, rural)	585	102	59.67	181.99 (d)	185.10	**1545.10**
ICS Taïba – Dakar	Diesel train, heavy bulk, long	18	17	0.31	0.93 (d)	0.93	**1360.93**

(a) Well-to-wheel, CE (2016b).

(b) Multiplied by a factor 2; 2 tonnes of ore are transported per tonne of phosphate rock (section 3.2).

(c) Kool et al., 2012.

(d) Assuming 3.05 tonnes of PR are needed for production of one tonne of P_2O_5 (EFMA, 2000).

5.3 Comparison of total emissions

Total emissions from production of struvite in the Netherlands and subsequent transport to the ports of Dakar, Lomé and Abidjan, calculated from Table 6 and GHG emissions from struvite production of -0.35 kg CO_2 eq. kg^{-1} of struvite (section 5.1.2), are summarized in Table 9. Negative GHG emissions from struvite production outweigh (positive) transport emissions by far, resulting in negative overall emissions for the whole chain (production + transport). Assuming transport with Handymax-like vessels, average GHG emissions from production and transport of struvite to Dakar, Abidjan and Lomé are -820, -596 and -536 kg CO_2 eq. per tonne of P_2O_5 respectively. Hence, net GHG emission reductions are calculated for all three scenarios. The greatest emission reductions are realised by exporting struvite to Dakar, as it is the closest to Rotterdam of the three ports that were compared, hence emissions from ocean shipping are lowest.

Table 9 *Estimated GHG emissions from production of struvite at SWTPs in the Netherlands and subsequent transport to the ports of Dakar, Lomé and Abidjan.*

Section	Transport mode	Dist. (a) km	WTW GHG Emission Factor (b) g CO_2 eq. $t^{-1}km^{-1}$	WTW GHG emissions transport, 1 TEU, section (c) kg CO_2 eq.	WTW GHG emissions transport, 1 tonne of struvite, section (d) kg CO_2 eq.	WTW GHG emissions transport, totals from Apeldoorn, 1 tonne of struvite kg CO_2 eq.	Total GHG emissions, transport & production, 1 tonne of struvite kg CO_2 eq.	Total GHG emissions, transport & production, 1 tonne of P_2O_5 (e) kg CO_2 eq.
(Production of struvite)	**-**	-	-	-	**-350**	-	-	-
Apeldoorn-Rotterdam	Tractor-semitrailer (2 TEU)	175	102	407	20	20	-330	**-1320**
Maastricht-Rotterdam	Tractor-semitrailer (2 TEU)	200	102	465	23	-	-327	**-1309**
Rotterdam-Dakar	Handymax vessel	4863	23	2550	125	145	-205	**-820**
Rotterdam-Abidjan	Handymax vessel	7039	23	3691	181	201	-149	**-596**
Rotterdam-Lomé	Handymax vessel	7628	23	4000	196	216	-134	**-536**

(a) Distance based on http://www.marinetraffic.com/en/voyage-planner; 1 NM = 1.852 km.

(b) Well-to-wheel, CE (2016b).

(c) Gross weight of a TEU containing 12 big bags of struvite is 22.8 tonnes (Table 5).

(d) Net weight of 12 big bags of struvite is 20.4 tonnes (Table 5).

(e) Assuming 25% P_2O_5 content (Table 1, WVV/SWTP Apeldoorn).

5.4 Discussion and conclusions

Based on limited data of GHG emissions from P fertilizer production and assuming equal crop effectiveness of P in struvite and mineral fertilizers, replacing soluble mineral P fertilizers in West Africa with struvite from the Netherlands may result in substantial GHG emission reductions (Table 10). Emissions from production of mineral fertilizers in West Africa and transport to Dakar and Lomé were estimated at 1.36 tonne CO_2 eq. per tonne of P_2O_5 (Table 8). Emissions from production in Togo and transport to Abidjan were higher (1.55 tonne CO_2 eq. per tonne of P_2O_5) due to the required road transport. Emissions from producing struvite in SWTPs in the Netherlands and subsequent transport to West Africa were estimated at -0.82, -0.60 and -0.54 tonne CO_2 eq. per tonne of P_2O_5 respectively (Table 9). Hence, the potential emission reduction from replacing mineral P fertilizers with imported struvite is **2.18 (Dakar), 2.14 (Abidjan) and 1.90 (Lomé) tonne CO_2 eq. per tonne of P_2O_5**.

Table 10 *Overall emissions from production and transport of struvite and mineral P fertilizers, and GHG emission savings from replacing mineral P fertilizers with struvite.*

Destination, product and origin	Total GHG emissions, transport + production (t CO_2 eq. per t of P_2O_5)	GHG savings from replacing mineral P fertilizers with struvite (t CO_2 eq. per t of P_2O_5)
Dakar, mineral P fertilizer from ICS Taiba	1.36	
Dakar, struvite from WVV Apeldoorn	-0.82	**2.18**
Abidjan, mineral P fertilizer from SNPT Hahotoé, Togo	1.55	
Abidjan, struvite from WVV Apeldoorn	-0.60	**2.14**
Lomé, mineral P fertilizer from SNPT Hahotoé	1.36	
Lomé, struvite from WVV Apeldoorn	-0.54	**1.90**

Given an annual struvite production of 700 tonnes (175 tonnes of P_2O_5, Table 1), the annual GHG reduction achieved by use of struvite from SWTP Apeldoorn in West Africa could range between **~333 and ~382 tonnes of CO_2 eq.** Emission reductions are greatest for Dakar, as that port is located closest to the Netherlands hence has lowest shipping emissions. Emission reductions for export to Abidjan (Cote d'Ivoire) are greater than to Lomé (Togo), as Cote d'Ivoire has no domestic P fertilizer production. We therefore assumed that regional P fertilizers were imported from nearby Togo by road, resulting in substantial transport emissions. Hence, the emission reduction achieved by replacing the product with struvite are also greater.

GHG emissions from transport are greatly outweighed by those from production of mineral P fertilizers and struvite. Using correct emissions data for fertilizer production is critical therefore. In absence of better data, we used a global average figure of the GHG emissions from P fertilizer production of 1.36 kg CO_2 eq. kg^{-1} of P_2O_5 (Kool et al., 2012). However, Kool et al. (2012) also indicate that, in the most favourable cases, GHG emissions from production of TSP and SSP can be much lower and even negative. If the P fertilizer industry in West Africa is modernized, emissions from P fertilizer production may become much lower than we assumed, potentially even negative. It seems reasonable to expect emissions at least comparable to those of Europe in the foreseeable future. We recalculated the GHG emissions in Table 8, now assuming GHG emissions from production of P fertilizers of 0.56 (Brentrup and Pallière, 2015) instead of 1.36 kg CO_2 eq. kg^{-1} of P_2O_5. Results are given in Table 11. Overall emissions are now less than half of those in Table 8, ranging between 0.56 and 0.74 kg CO_2 eq. kg^{-1} of P_2O_5.

Table 11 *Estimated GHG emissions from production of P fertilizers in Senegal and Togo and subsequent transport to the ports of Dakar, Lomé and Abidjan - P fertilizer production with reduced GHG emissions.*

Section	Transport mode	Distance km	WTW GHG Emission Factor (a) g CO_2 eq. $t^{-1}km^{-1}$)	WTW GHG emissions transport, 1 tonne of PR, section kg CO_2 eq.	WTW GHG emissions transport, 1 tonne of P_2O_5, section kg CO_2 eq.	Total WTW GHG emissions transport 1 tonne of P_2O_5 kg CO_2 eq.	Total GHG emissions, transport + production, 1 tonne of P_2O_5 (c) kg CO_2 eq.
(Production of P fertilizers)	-	-	-	-	**560**	-	-
SNPT Hahotoé – Kpeme (Lomé)	Diesel train, heavy bulk, long	30	17	1.02	3.11	3.11	**563.11**
SNPT Hahotoé – Abidjan (Ivory Coast)	Diesel train, heavy bulk, long	30	17	1.02	3.11	-	-
	Tractor-semitrailer (heavy bulk, rural)	585	102	59.67	181.99	185.10	**745.10**
ICS Taïba – Dakar	Diesel train, heavy bulk, long	18	17	0.31	0.93	0.93	**560.93**

(a) CE, 2016b.

(b) EF multiplied by 2; 2 tonnes of ore are transported per tonne of phosphate rock (section 3.2).

(c) Kool et al., 2012.

(d) Assuming 3.05 tonnes of PR are needed for production of one tonne of P_2O_5 (EFMA, 2000).

Similarly, most of the GHG emission credits from the production of struvite stem from the fact that with struvite production, iron chloride is no longer needed. However, once struvite production has become standard practice instead of removing P with iron chloride, the assumed savings in iron chloride compared to the 'standard process' seem no longer justified. If we estimate GHG emissions from struvite production only from its MgO requirement (0.20 kg CO_2-eq./kg struvite; CE, 2016a) and from the combustion of sludge (0.04 kg CO_2-eq./kg struvite; CE, 2016a), the result is a net GHG emission of 0.24 kg CO_2 eq. kg^{-1} of struvite, instead of emission reduction of -0.35 kg CO_2 eq. kg^{-1}. This positive value was now used in recalculating the overall emissions from struvite production and transport to West Africa (Table 12). Under these assumptions, total GHG emissions change from negative (Table 9) to markedly positive; in fact they are even higher than the values in Table 11, hence importing struvite from the Netherlands no longer results in emission savings compared with the use of mineral fertilizers produced in the region.

In conclusion, once struvite production has become standard practice, assuming GHG reductions from avoided iron chloride use may no longer justified. Also, a modernizing P fertilizer industry in Africa may over time lead to reduced or even negative GHG emissions from the production of soluble P fertilizers. Our calculations indicate that under such a scenario, using struvite from the Netherlands as a P fertilizer in West Africa may no longer contribute to GHG emission reduction and, on the contrary, aggravate emissions.

Table 12 *Estimated GHG emissions from production of struvite at SWTPs in the Netherlands and subsequent transport to the ports of Dakar, Lomé and Abidjan – without crediting struvite production with avoided use of iron chloride.*

Section	Transport mode	Dist. (a)	WTW GHG Emission Factor (b)	WTW GHG emissions transport 1 TEU, Section (c)	WTW GHG emissions transport, 1 tonne of struvite, section (d)	WTW GHG emissions, transport, totals from Apeldoorn, 1 tonne of struvite	Total GHG emissions. transport & production, 1 tonne of struvite	Total GHG emissions. transport & production, 1 tonne of P_2O_5 (e)
		km	g CO_2 eq. $t^{-1}km^{-1}$	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.
(Production of struvite)	-	-	-	-	**240**	-		
Apeldoorn-Rotterdam	Tractor-semitrailer (2 TEU)	175	102	407.0	20.0	20.0	260.0	**1039.8**
Maastricht-Rotterdam	Tractor-semitrailer (2 TEU)	200	102	465.1	22.8	22.8	262.8	**1051.2**
Rotterdam-Dakar	Handymax vessel, medium load	4863	23	2550.3	125.0	145.0	385.0	**1539.9**
Rotterdam-Abidjan	Handymax vessel, medium load	7039	23	3691.5	181.0	200.9	440.9	**1763.6**
Rotterdam-Lomé	Handymax vessel, medium load	7628	23	4000.3	196.1	216.0	456.0	**1824.2**

(a) Distance based on http://www.marinetraffic.com/en/voyage-planner; 1 NM = 1.852 km.

(b) Well-to-wheel, CE (2016b).

(c) Gross weight of a TEU containing 12 big bags of struvite is 22.8 tonnes (Table 5).

(d) Net weight of 12 big bags of struvite is 20.4 tonnes (Table 5).

(e) Assuming 25% P_2O_5 content (Table 1, WVV/SWTP Apeldoorn).

6 Legal issues related to trade and use as fertilizer

6.1 General background

The conditions for trade, transport and use of struvite are governed by rules and regulations at EU and national level, and this is determined by the legal status of the struvite. Struvite produced from sewage sludge can be classified either as an EC-fertiliser under Regulation (EC) 2003/2003 relating to fertilisers, or as a regained phosphate fertiliser under the Dutch Fertiliser Act. Or, if it doesn't comply to either of those two, as a waste. The legal status of struvite is mainly determined by its composition, most importantly the contents of organic matter, phosphate and nitrogen.

The most important regulations are:

1. Waste Framework Directive 2008/98/EC on waste: sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery. In the Netherlands, the Waste Framework Directive is implemented via the Environmental Protection Act
2. Fertiliser Regulation: Regulation (EC) 2003/2003 relating to fertilisers lays down definitions and requirements for products that are placed on the market as EC fertilisers
3. Fertiliser Act: Dutch act laying down the definitions and criteria for products that are placed on the Dutch market as fertilisers or soil improvers
4. Waste Shipments Regulation EC Regulation (EC) No 1013/2006 on shipments of waste: lays down procedures for the transboundary shipments of waste. It also incorporates the provisions of the Basel Convention and the revision of the OECD's 2001 decision on the control of transboundary movements of wastes destined for recovery operations
5. Third countries regulation: commission regulation (EC) No 1418/2007 concerning the export for recovery of certain waste listed in Annex III or IIIA to Regulation (EC) No 1013/2006 of the European Parliament and of the Council to certain countries to which the OECD Decision on the control of transboundary movements of wastes does not apply; amended by Regulation (EC) 733/2014
6. CLP Regulation (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures
7. REACH: Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals

The composition of several struvites from Dutch sewage sludge installations has been investigated by Morgenscheis et al. (2015), see Table 12. There were considerable differences in composition. The composition from two (out of the four) struvites from this study will be used here as reference and compared with the struvite from the production location in Apeldoorn of water board Vallei en Veluwe. All three struvites were produced with the NURESIS technology:

A. Struvite from Land van Cuijk was comparable to pure struvite: it contained N, MgO and P_2O_5 in concentrations comparable to pure struvite and no measurable amounts of organic carbon(<0,5% organic matter).
B. The struvite from Leuven contained 8,4% organic matter, and lower contents of N and MgO than pure struvite. The water solubility of the P_2O_5 was high.
C. The struvite from Apeldoorn was comparable to that from Leuven, but contained no measurable amounts of organic carbon (<0.5% C).
D. Composition of the struvite product Chrystal Green, produced with the Pearl technology by Ostara was close to that of pure struvite.

Table 13 *Contents of agricultural relevant components in struvites produced in the Netherlands (Morgenschweis et al. 2016).*

Element (%)	Land van Cuijk	Leuven	Apeldoorn	Chrystal Green	Pure struvite
Dry matter (40 °C)	94	90.8	n.a.		
Dry matter (105 °C)	52	52.1	49.7		
Total organic carbon (TOC)	<0.5	4.2	<0.5	0	
N-total	5.2	1.82	1.8	5	5.7
P_2O_5-mineral acid	29	25	25	28	29
P_2O_5 NAC**	27	25	22		
P_2O_5 water	0.5	11	10		
MgO	17	13	15	16	16
CaO	0.1	0.2	0.1		

* organic matter =2*TOC.

** NAC = neutral ammonium citrate and water.

6.2 Struvite: waste or fertiliser?

Struvite from SWTPs are produced from a waste stream, hence are by definition a waste. According to the Waste Framework Directive 2008/98/EC, waste can cease to be waste when it has undergone a recovery operation and complies with specific criteria.

Currently, there are no specific End of Waste criteria defined for struvite at the EU or national level. Therefore, the end of waste status for struvite products can only be declared at the level of specific producers and a defined product.

In first instance, it is responsibility of the producer of the intended end-of-waste product to assess the status of the product: waste or product. After the producer has come to a judgment, it is then up to the competent authority to assess whether the product can be declared an end-of-waste product or not. The competent authority in the Netherlands is the Ministry of Infrastructure and Environment.

The general criteria that have to be satisfied for an End-of Waste status are:
1. the substance or object is commonly used for specific purposes;
2. there is an existing market or demand for the substance or object;
3. the use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products;
4. the use will not lead to overall adverse environmental or human health impacts.

Ad 1, 2. Struvite complies with the first two criteria: struvite is commonly used as a fertiliser, and there is an existing market and demand for the substance.

Ad 3. The criteria on lawful use implicates that the struvite has to comply with regulations regarding fertilisers. These are laid down in either the EC 2003/2003 at the EU level, or, at the national level in the Netherlands, the Dutch Fertiliser Act.

Ad 4. Also, the use as a fertiliser of struvite derived from communal waste water treatment plants should not result in adverse environmental or human health impacts.

6.3 Is struvite an EC fertiliser?

Struvite can be classified as an EC-fertiliser if it complies to the definitions and requirements laid down in Fertiliser Regulation EC 2003/2003.

It could qualify as an EC fertiliser, type: NP fertiliser B.2.1.
- Minimum nutrient contents (mass percentages): >3% N, >5% P_2O_5 and $\sum(N + P_2O_5) > 18\%$.

- Method of production: Product obtained chemically or by blending without addition of organic nutrients of animal or vegetable origin.

Pure struvite meets the nutrient requirements as it contains 5.7% N, and 29% P_2O_5. However not all struvite products are chemically pure struvites: the product C (water board Vallei en Veluwe) contains only 1.8% N. Therefore, it does not meet the criteria on minimum contents of nutrients (N>3%) for EC fertiliser type B.2.1.

Under 'method of production' it is stated that no organic nutrients of animal or vegetable origin may be added. The EC is very strict in the interpretation of this rule, which implies that EC fertilisers cannot contain any organic matter because this will always contain at least traces of nutrients of animal or plant origin.

Conclusion: struvite products that do not contain any organic matter and contain the minimum nutrient contents can be marketed as EC fertilisers type NP fertiliser B.2.1. This is only the case for product A (from Land van Cuijk). Product B contains organic matter (4,2% organic C), and will not be classified as EC fertilizer for that reason. Although the struvite product C (water board Vallei en Veluwe) does not contain organic matter (<0,5% organic C), it cannot be classified as an EU fertilizer type NP fertilizer B.2.1, because the N content is lower than 3%. Up to now, only the struvite product D. (Crystal Green of Ostara) has explicitly been granted permission to be marketed as an EC fertiliser.

The EC-fertiliser regulation 2003/2003 is currently under revision. Struvite is one of the products for which the JRC (Joint Research Centre) is carrying out a research, which is aimed to advice the European Commission on possible recovery rules. Struvite that classifies as an EC-fertiliser can be considered as a product that fulfils all required criteria for obtaining the End-of Waste status. This however still needs to be verified and approved by the Ministry of Infrastructure and Environment, Rijkswaterstaat Leefomgeving.

6.4 Is struvite a regained phosphate?

Most struvite products contain organic matter and are therefore -by definition- no EC fertiliser. These products can be traded and used in the Netherlands as a Regained Phosphate Fertiliser if they comply to the definition and criteria laid down in the Fertiliser Act, Implementation Degree and Implementation Regulation for Regained Phosphates.

Regained Phosphates include struvite, and are defined as:
1. Struvite, mainly consisting of magnesium ammonium phosphate that is formed during the purification of industrial process water or domestic, urban or industrial effluent or other waste water by precipitation with dissolved magnesium, ammonium or potassium.
2. Magnesium phosphate, resulting from the pasteurization or drying of struvite.
3. Dicalcium phosphate, mainly consisting of dicalcium phosphate, resulting from the purification of domestic, urban or industrial effluent or other waste water by precipitation with dissolved calcium.

The term "struvite, mainly consisting of magnesium ammonium phosphate" is not further defined. It is generally interpreted as referring to the end products resulting from the precipitation with magnesium, ammonium or potassium rather than to chemically pure struvite. Also, no minimum percentage is given for the content of phosphate of other nutrients in the regained phosphates.
There are limits for contents of heavy metals, arsenic and organic micro-contaminants, which are expressed per kg P_2O_5 in the struvite.
In addition, the struvite products originating from the sewage water treatment plants have to be treated in such a way that the majority of pathogens are killed. No procedure is prescribed and no specific criteria are set. Up till this moment, no affordable and effective method has been put forward. Complicating factor is that the struvite should not be heated above 55ºC. At higher temperatures, the ammonium and crystal water will evaporate, resulting in magnesium phosphate that is generally considered to be insoluble.

Struvite products that comply to the criteria for Regained Phosphates can be traded, transported and used as a fertiliser in the Netherlands. It is legally still considered waste, but for the trade, transport and use as fertiliser *in the Netherlands* it is exempted from the obligations arising from the Waste Framework EC Directive and the Dutch Environmental Protection Act.

Struvite product A consists for 97% of struvite, which will satisfy the term mainly. In fact, if the organic matter content can be shown to be negligible it might classify as an EG fertilizer (see before). In struvite products B and C the percentage of chemically pure struvite is maximally 35% (based on N content). The struvite products do contain other phosphate precipitation products as can be seen from the percentage P_2O_5. Water solubility of struvite products B and C is high compared to struvite A.

Struvite products that can be classified as a Regained Phosphate fulfil the first three criteria of the End of Waste status. However, the competent authority in this case (Ministry of Infrastructure and Environment, Rijkswaterstaat Leefomgeving) is not satisfied that the use will not lead to overall adverse environmental or human health impacts. In particular, concerns about possible traces of medicines and pathogens in the struvite have been expressed.

6.5 Requirements for shipments of struvite products

Without the End-of- Waste declaration, struvite products are legally still considered waste. The export and transboundary transport of waste is regulated by the EC Waste Shipments Regulation.

A distinction is made between EU countries, OECD countries and the so-called third countries (non OECD countries). The West African countries are third countries.

Export of waste to third countries is more restricted than export to EU or OECD countries. The conditions for export are also determined by the classification of waste. Waste is classified according to the Annexes of the Waste Shipment Regulation, based on the Basel/OECD codes and Eural waste codes.

- Annex III contains the 'Green list' of wastes that are considered non-hazardous.
- Annex IV contains the Amber list, consisting of both hazardous and non-hazardous waste.
- Annex V lists the hazardous wastes that are not allowed to be exported to third countries.

For waste of the Green list, the requirements for export of waste to third countries is regulated via the Third countries regulation, which Senegal has subscribed to. This however does not apply to the export of waste from the Amber list.

For struvite produced from sewage sludge the Basel code AC270 'sewage sludge' and the Eural codes 190805 'sewage sludge from communal waste water treatment', or 190899 'waste from water treatment plants not classified elsewhere', can be considered to be most relevant.

Waste with code AC270 is listed in annex IV, the Amber list. These wastes can only be exported to third countries for recovery if they are not listed as hazardous on annex V. Waste with Eural codes 190805 and 190899 is not considered hazardous according to annex V, and is therefore not excluded from export to non-OECD countries.

For the export of waste from the amber list for recovery to third countries, the procedure of prior written notification and consent for shipments of wastes is in order.
The exporting party has to notify the competent authority in the country of origin. All necessary documentation should be provided by the exporting party. The competent authority in the Netherlands is the ILT (Inspectiedienst Transport en Leefomgeving).
The documentation should include a legally enforceable, written contract with the business that will be recovering the notified waste.

This contract must include:

- a certificate from the business recovering or disposing of the waste, confirming they have legally recovered or disposed of the waste
- an obligation for the notifier to take the waste back if the shipment, recovery or disposal does not go ahead as intended, or if the shipment is illegal
- an obligation for the importer (consignee) to recover or dispose of the waste if it is found to be illegal as a result of the consignee's action.

The competent authority will assess the notification and contact the country of destination (and transit). Both countries have to approve the export. It is for the importing country to specify what they require in terms of certification, some countries require confirmation that the material is deemed acceptable to the authorities in the country of origin.

In addition, the exporting party has to be able to show an approved financial guarantee or insurance that must be sufficient to cover the cost in case the shipment isn't completed, including the cost of returning the exported waste.

If consent is given, a certificate will be issued for the transport of a load of the waste by a certified transport company on a set date.

6.6 Does struvite need to be REACH registered?

All chemical substances that companies in the EU manufacture or import above one tonne a year have to be registered under REACH. Companies are responsible for collecting information on the properties and uses of the substances, and have to assess the hazards and potential risks presented by the substance.

Registration is based on the "one substance, one registration" principle. This means that manufacturers of the same substance have to submit their registration jointly. The analytical and spectral information provided should be consistent and sufficient to confirm the substance identity.

REACH facilitates regulatory formalities for "recovered substances": substances that result from a recovery process in the Community and that are the same as a substance that has already been registered are exempted from the obligation to register. Struvite has been REACH registered by Berliner Wasserbetriebe. For other struvite producers this would mean that they are not obliged to complete a separate registration as long as sameness of their struvite product to that of Berliner Wasserbetriebe can be demonstrated. They will need to gain access to the registration by Berliner Wasserbetriebe.

Struvite is registered in the REACH database as ammonium magnesium orthophosphate (hexahydrate), molecular formula: H3-N.H3-O4-P.Mg 100% crystalline inorganic material, odourless, relative density of 1.77. Physical and chemical properties: Mono constituent substance, solid state at 20°C, 0 impurities or additives relevant for classification. EC number 232-075-2; CAS Number:7785-21-9. Active registration by Berliner Wasserbetriebe, Aarhus and Hoogheemraadschap Amstel Gooi en Vecht (Registration numbers 01-2119983188-23-0000, 01-2119983188-23-0001, 01-2119983188-23-0002).

Table 14 *Characterisation of struvite.*

Status	EC 2003/2003	Dutch Fertiliser Act	Waste	Waste shipment	Transport	REACH
EC fertiliser	Yes	Yes	N?	N?	NORMAL?	Yes
Regained Phosphate	No	Yes	Yes	Yes	WASTE	Yes
Waste	No	No	Yes	Yes	WASTE	No

Only struvite that is classified as a product (fertiliser) needs a REACH registration. Waste is not seen a product and therefore does not need a REACH registration.

6.7 Labelling and packaging of struvite products

Producers and exporters (distributors) are responsible for the evaluation, classification, labelling and packaging of their products. The labelling and packaging of products and substances in the EU is regulated by CLP Regulation (EC) No 1272/2008. This regulation anchors the UN-GHS into EU law. The Globally Harmonised System addresses the classification of chemicals by types of hazard. It aims at ensuring that information on physical hazards and toxicity from chemicals be available in order to enhance the protection of human health and the environment during the handling, transport and use of these chemicals. It includes hazard communication elements, including label instructions and safety data sheets.

6.8 Import requirements and documentation in Senegal

Senegal implemented the WTO Agreement on Customs Valuation in July 2001 which provides for a neutral and uniform system for the valuation of goods for customs purposes. However, Senegal’s 2001 designation as an LDC (Less Developed Country) by the United Nations has incited officials to continue to apply minimum reference prices for some imported products that may hurt local industry.

In January 2000, Senegal put in place a new import tariff structure to conform with the common external tariff (CET) scheme agreed upon by the member states of the West African Economic and Monetary Union (WAEMU or UEMOA). No special import regulations or standards for fertilisers have been found.

The import requirements and documents required when exporting products to Senegal (summarized by the US commercial service, 2014)include the following:

Import procedures:
1. Importers must deposit a Preliminary Import Declaration seven days before shipping imported goods having a value equal to or greater than CFAF one million.
2. Automatic approval of the Preliminary Import Declaration is obtained by submitting three copies of the Pro Forma Bills of Lading with the declaration.
3. A Preliminary Import Declaration is valid for six months and can be extended for three months. Preliminary Import Declarations must be canceled and reissued if there is a change in supplier, an increase in the value of the order of more than ten percent, or a modification in the quantity of the order.
4. Any payment for imported goods greater in value than CFAF one million must be made through an approved Senegalese bank or financial institution.
5. Any FOB import value equal to or greater in value than CFAF three million must be inspected by the PSI company in the supplier’s country before shipping.
6. Presentation of a clean report of findings issued by the PSI firm is obligatory.
7. The Pre-Shipment Inspection Certificate.

Some goods are exempted from PSI, among which:
- Imports with a total order FOB value equal to or below CFAF 3 million
- Goods imported by certain importers which have a special exemption authorization from the Government

Documentation:
1. Two copies of the commercial invoice which should identify the exporter and importer as well as their addresses; the goods being imported; the weight, CIF value and quantity of goods imported;

and a complete description of the merchandise. This should be in French or accompanied by a French translation to avoid misinterpretation at the customs entry point.

2. A Pro Forma Invoice. This should contain the same information as the commercial invoice.
3. A Certificate of Origin is necessary for all imported goods. Before shipping, importers must provide customs officials with documentation listing the quantity, quality and prices of the products subject to customs duties.

6.9 Conclusions

The export of struvite to West African countries is governed by a range of EU and national regulations. Transport of struvite that has not reached the End of Waste status is an administratively complicated and time consuming process.

The export of struvite that classifies as EC fertiliser seems most promising. The End of Waste status seems relatively easily attainable. Also, both chemically pure and non-pure struvites classify as EC fertilizer, as long as they contain no organic matter and fulfil criteria on nutrient content.

The export of struvite that classifies as regained phosphate fertiliser in the Dutch Fertiliser Act is complicated by the waste status. In the short term, no End of Waste status is foreseen.
Another complication is that the struvite has to be sanitised to kill human pathogens. No affordable and effective method has been put forward yet.

7 General discussion and conclusions

Struvite from the Netherlands can generally be supplied to West African ports below (P_2O_5 –based) world market prices of soluble mineral P fertilizers. Whether there is real opportunity for a profitable trade remains uncertain however, as the prices that blenders, traders and importers are presently paying for P fertilizers are unclear. Also, in attempting to contact importers and traders, no response was obtained, which may point at a general lack of interest in importing P fertilizers.

Struvite is not able to compete with rock phosphate, based on its (P_2O_5 –based) world market price. However, rock phosphate is less practical to work with due to its powdery substance and is a slow release P fertilizer. If finely ground, struvite has similar effectiveness and quick-release properties as soluble mineral P fertilizers. When struvite is applied in the form of course granules, it behaves as a slow-release P fertilizer but probably is easier to transport and to work with than rock phosphate.

A factor that needs to be taken into account when planning to initiate struvite export is that most West African countries currently import only small quantities of P fertilizers. Several countries, particularly Senegal and Togo, have their own P mines; in addition, Senegal also produces soluble P fertilizers. Most of this production is for export however. If part of it were available to local blenders and traders below world-market prices, then it would be more difficult for imported struvite to compete.

To African traders and producers, export of P fertilizers may be much more lucrative than local marketing and may also substantially contribute to the GDP. On the other hand, a large share of the economic benefits may accrue to foreign investors whilst West African smallholders urgently need more P fertilizers. Making struvite available on the local market might be able to bring about a small change in the current status quo. The conclusion that Schreiber and Matlock (1978) drew after inventorying the phosphate industry in North and West Africa after all seem still valid today, and may extend to struvite: "phosphate utilization in the region needs to be improved and it may be possible to substitute locally obtained crushed rock (or struvite!) for expensive imported fertilizers'. A prerequisite is that these products should be clean and safe (contents of impurities such as heavy metals should be within legal and advisable limits). Appendix I provides an impression of the quality of the struvite produced at SWTP Apeldoorn (water board Vallei en Veluwe) in the Netherlands.

Replacing P fertilizers that are produced regionally in West Africa with struvite from the Netherlands may result in GHG emissions savings of ~2 tonne CO_2 eq. per tonne of P_2O_5. GHG savings are inversely related to the distance between Rotterdam and the port of destination hence are greatest for Dakar, intermediate for Abidjan and smallest for Lomé. In absence of better data, our estimate is based on a global average GHG intensity of P fertilizer production of 1.36 kg CO_2 eq. kg^{-1} of P_2O_5 and (negative) GHG emissions from struvite production in the Netherlands of -0.35 kg CO_2 eq. kg^{-1} of struvite. Replacing P fertilizers from further away, e.g. from Morocco, may yield greater GHG savings if similar emissions from production are assumed, as the greater transport distance will cause greater transport GHG emissions. GHG emission data of P fertilizer production in specific countries or by specific producers are largely unavailable. Although emissions from the use of N fertilizer in agriculture are generally far greater than from P fertilizers, greater transparency in terms of GHG emissions could still aid decision making in the context of climate smart agriculture.

Over time, GHG emission savings from importing struvite from the Netherlands may diminish or disappear, if P fertilizer production in Africa becomes more efficient and its GHG emissions is reduced or even becomes negative. Also, struvite production may become commonplace in the Netherlands. Crediting it with avoided use of iron chloride (to remove P from wastewater) would then no longer be justified and struvite production emissions might turn positive instead of negative. Therefore, a trade in struvite should be seen as a transitional measure. In the longer run, it seems preferable for struvite

to be produced in sewage water treatment installations in Africa itself, contributing to the creation of a local circular economy local nutrient cycling.
Apart from a low price and reduced GHG emissions, substituting mineral P fertilizers with struvite may have other environmental benefits. For instance, phosphate rock production in Togo leads to the discarding of up to 500,000 tonnes of phosphate fines are into the Gulf of Guinea/Benin, annually. High concentrations of Cd, Cr, Pb, Zn, Cu and Ni have been measured in the coastal sediments near the dumping site. Cd is easily mobilized in seawater and thus pollutes much larger areas of the Gulf of Guinea/Benin. Efforts should be made to substantially reduce the disposal of phosphatic material into the ocean, and develop low-cost phosphatic soil amendments from these 'waste' materials (Van Straaten, 2002). Such drawbacks are not associated with the production of struvite.

Because fertilization increases the risk of Cd movement into the food chain, several countries have implemented regulations limiting the amount of Cd that can be present in P fertilizers (Robberts, 2014). Cd contents of several West African rock phosphates are elevated. This is the case with rock phosphate from from Taïba and Thies in Senegal for instance. Cd concentrations in rock phosphate from Togo are greater than that permitted for use in Western Europe (Van Straaten, 2002). Heavy metal content of struvite (e.g. Appendix I), in contrast, is generally much lower than that of mineral P fertilizers.

The export of struvite to West African countries is governed by a range of EU and national regulations. Transport of struvite that has not reached the End of Waste status is an administratively complicated and time consuming process. The export of struvite that classifies as EC fertiliser seems most promising therefore. The End of Waste status seems relatively easily attainable. Both chemically pure and non-pure struvites classify as EC fertilizer, as long as they contain no organic matter and fulfil criteria on nutrient content.

An aspect that has remained unclear is the cultural acceptability of using struvite from SWTPs in the Netherlands as a fertilizer in Africa. Depending on local culture, use of human excreta as a fertilizer in Africa may subject to cultural taboos. The best and perhaps only way to find out whether struvite, a clean and odourless product after all, would be acceptable to African farmers is to set up a pilot with the product in farmers' fields in Africa. Such a pilot could include the export process from the Netherlands and import in West Africa and all the required paperwork, hence provide a first indication of practical feasibility. The field experiments would also serve to reconfirm and demonstrate the effectiveness of struvite vis-a-vis other fertilizers to local farmers. In order to realize such an effort, considerable time and momentum may be required and the participation of a large partner with substantial negotiating and lobbying power, either from the private sector or a NGO, seems a *sine qua non.*

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Annex 1 Chemical Analysis of Struvite from SWTP Apeldoorn

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Vallei en Veluwe
17 OKT 2016

Prüfbericht

Auftrags-Nr.:	-
Labor-Nr. :	DD 1604625
Seite 1 von 2	

Hameln, 12.10.2016 -ge
Auskunft: Dr. Paradies-Severin
Telefon 05151/9871-53

Bezeichnung: Struvite
(nach Angabe des Einsenders)
Typ/Menge: 1686 g incl. Verp.
Eingangsdatum: 06.09.2016 Verpackung: Polygefäß, ohne
Beginn der Prüfung: 06.09.2016
Ende der Prüfung: 10.10.2016 Probenahmebericht-Nr.:
Datum
der Herstellung: Probenehmer: Pn d. Auftraggeber
der Lieferung:
der Probenahme:

Parameter		**Deklaration**	**Befund im Original**	**Befund in Trockenmasse**
Trockensubstanz Methode: DIN EN 12880, S 2a	%		49,74	
Gesamt-Stickstoff Methode: VDLUFA II, 3.5.2.7	%		1,81	3,64
P2O5 (mineralsäurelöslich) Methode: ISO 11885, E 22	%		25,51	51,29
P2O5 neutralammoncitratlsl. Methode: ISO 11885, E 22	%		21,98	44,19
P2O5 (wasserlöslich) Methode: ISO 11885, E 22	%		10,04	20,18
Magnesium (MgO) Methode: ISO 11885, E 22	%		15,08	30,32
Calcium (CaO) Methode: ISO 11885, E 22	%		0,07	0,14
Organische Substanz (C-org.) Methode: VDLUFA II, 1.10.2	%		<0,5	<0,5
Kupfer Methode: ISO 11885, E 22	mg/kg		1,49	3,0
Zink Methode: ISO 11885, E 22	mg/kg		3,98	8,0

Umrechnung: 1 % = 10.000 mg/kg

„< ...“ = Wert ist kleiner als die nebenstehende untere Grenze des Arbeitsbereichs.
#1 = LUFA Standort OL, Jägerstr. 23-27; #2 = LUFA Standort OL, Ammerländer Heerstr. 123; #3 = LUFA Standort OL, Ammerländer Heerstr. 115-117; #5 Untersuchung erfolgte durch Fremdlabor; #6 = unterliegt nicht der Akkreditierung

Die Untersuchungsergebnisse beziehen sich ausschließlich auf das uns vorliegende Probenmaterial. Dieser Prüfbericht darf nur vollständig ohne unsere schriftliche Genehmigung vervielfältigt bzw. weitergegeben werden.

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DAkkS Deutsche Akkreditierungsstelle D-PL-14165-01-00

LUFA NORD-WEST

Labor-Nr. DD 1604625	vom 12.10.2016	Seite 2 von 2

Schadstoffe (DüMV Anlage 2, Tab. 1.4)		**Deklaration**	**Befund im Original**	**Befund in Trockenmasse**
Arsen Methode: ISO 17294-2, E 29	mg/kg			0,15
Blei Methode: ISO 17294-2, E 29	mg/kg			<1,0
Cadmium Methode: ISO 17294-2, E 29	mg/kg			<0,10
Chrom Methode: ISO 11885, E 22	mg/kg			10,0
Nickel Methode: ISO 11885, E 22	mg/kg			4,0
Quecksilber Methode: DIN EN 1483, E 12	mg/kg			0,01

Bemerkungen: Weitere Parameter siehe Anlage.

In Vertretung

Dr. Inge Paradies-Severin
(Laborleiterin)

Umrechnung: 1 % = 10.000 mg/kg

„< ...“ = Wert ist kleiner als die nebenstehende untere Grenze des Arbeitsbereichs.
#1 = LUFA Standort OL, Jägerstr. 23-27; #2 = LUFA Standort OL, Ammerländer Heerstr. 123; #3 = LUFA Standort OL, Ammerländer Heerstr. 115-117; #5 Untersuchung erfolgte durch Fremdlabor; #6 = unterliegt nicht der Akkreditierung

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Anlage 1 zum Prüfbericht vom 12.10.2016

Labor-Nr.: DDM 1604625
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Bezeichnung: **Struvite**
(nach Angabe des Einsenders)

Untersuchungsergebnis		< = kleiner als	Methode
CKW	in Originalsubstanz		VDLUFA VII, 3.3.2
HCB		< 0,01 mg/kg	
alpha-HCH		< 0,01 mg/kg	
beta-HCH		< 0,01 mg/kg	
gamma-HCH		< 0,01 mg/kg	
delta-HCH		< 0,01 mg/kg	
Heptachlor		< 0,01 mg/kg	
trans-Heptachlorexpoxid		< 0,01 mg/kg	
Aldrin		< 0,01 mg/kg	
Dieldrin		< 0,01 mg/kg	
Endrin		< 0,01 mg/kg	
Isodrin		< 0,01 mg/kg	
alpha-Endosulfan		< 0,01 mg/kg	
beta-Endosulfan		< 0,01 mg/kg	
op-DDE		< 0,01 mg/kg	
pp-DDE		< 0,01 mg/kg	
op-DDD		< 0,01 mg/kg	
pp-DDD		< 0,01 mg/kg	
op-DDT		< 0,01 mg/kg	
pp-DDT		< 0,01 mg/kg	
PCB	in Originalsubstanz		VDLUFA VII, 3.3.2
PCB 28		< 0,01 mg/kg	
PCB 52		< 0,01 mg/kg	
PCB 101		< 0,01 mg/kg	
PCB 118		< 0,01 mg/kg	
PCB 138		< 0,01 mg/kg	
PCB 153		< 0,01 mg/kg	
PCB 180		< 0,01 mg/kg	
MKW	in Originalsubstanz		DIN ISO 16703
Kohlenwasserstoffe		< 100 mg/kg	

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Anlage 1 zum Prüfbericht vom 12.10.2016

Labor-Nr.: DDM 1604625
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Bezeichnung: **Struvite**
(nach Angabe des Einsenders)

Untersuchungsergebnis < = kleiner als Methode

PAK	in Originalsubstanz	VDLUFA VII, 3.3.3
Naphthalin	< 0,05 mg/kg	
Acenaphthylen	< 0,05 mg/kg	
Acenaphthen	< 0,05 mg/kg	
Fluoren	< 0,05 mg/kg	
Phenanthren	< 0,05 mg/kg	
Anthracen	< 0,05 mg/kg	
Fluoranthen	< 0,05 mg/kg	
Pyren	< 0,05 mg/kg	
Benz(a)anthracen	< 0,05 mg/kg	
Chrysen	< 0,05 mg/kg	
Benz(b)fluoranthen	< 0,05 mg/kg	
Benz(k)fluoranthen	< 0,05 mg/kg	
Benz(a)pyren	< 0,05 mg/kg	
Dibenz(ah)anthracen	< 0,05 mg/kg	
Benz(ghi)perylen	< 0,05 mg/kg	
Indeno(123-cd)pyren	< 0,05 mg/kg	
Summe PAK	< 0,05 mg/kg	

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Report WPR-673

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The mission of Wageningen University and Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to inding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 5,000 employees and 10,000 students, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.