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Phosphorus recovery from animal manure

Technical opportunities and agro-economical perspectives

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O.F. Schoumans, W.H. Rulkens, O. Oenema and P.A.I. Ehlert

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Abstract

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In this report, various options for phosphorus recovery from pig slurry in the Netherlands are evaluated. The studies have been made in co-operation with waste and phosphorus processing companies.

All options start with the separation of slurries in a liquid and solid fraction, with or without an initial anaerobic digestion for biogas recovery. The solid fraction contains most of the phosphorus and organic matter, and the liquid fraction contains most of the soluble salts including nitrogen. The solid fraction can be used directly for soil amendment, or for bio-energy production through incineration or pyrolysis with a subsequent recovery of phosphorus from ashes and biochar.

From a technical point of view, there are many opportunities for energy, phosphorus and nitrogen recovery from pig slurry via various processing treatments. However, the separation of manure in liquid and solid fractions, drying of the solid fraction and the transport of liquid and solid fractions are associated with relatively high economic costs. The agro-economical perspectives of manure processing highly depend on the prices of crude oil and phosphorus fertilizers, the environmental and legal restrictions and alternatives of manure disposal.

Keywords: manure, phosphate, phosphorus, recovery, treatment, separation, digestion, drying, incineration, pyrolysis, fertilizer, ash, biochar.

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Wageningen, December 2010

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Preface

This project was funded by the Ministry of Economic Affairs, Agriculture & Innovations in the Netherlands. The research was carried out in the period April 2009-December 2010. During the study we have had meetings and discussions with some representatives of various industries and organisations. We would like to thank them for their interests and contribution:

ICL-fertilizers EU	Anthony Zanelli en Kees Langeveld
THERMPHOS	Willem Schipper
SNB	Leon Korving
ECN	Jan Pels
Stowa	Cora Uijterlinde
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Furthermore, we would like to thank the project group “Mestinnovations” of Wageningen UR for the good discussions and the useful comments on the draft of this report. Special thanks to Hans Verkerk (CUMELA Nederland) for the information about the cost of manure transport.

The outcome of the study has been discussed with the former Minister of Agriculture, Nature and Food Quality, Gerda Verburg. We hope that the results will help the policy makers with their decisions regarding the reduction of the manure surplus in terms of phosphate. Furthermore, we hope that the discussed techniques and formulated options will lead to a more efficient recycling and reuse of phosphate. Since agricultural use more than 80% of the world wide phosphate production from rock phosphate mines, the mentioned approaches in this report can help to postpone the upcoming scarcity of phosphate.

The authors

Beleidssamenvatting

Voorspellingen geven aan dat de hoeveelheid dierlijke mest die in 2015 niet meer op de Nederlandse landbouwgronden geplaatst kan worden een equivalent van 40-60 miljoen kg fosfaat zal bedragen. Het actuele overschot aan dierlijke mest zal afhangen van de economische ontwikkelingen in de veehouderij, het succes van voederstrategieën om de stikstof- en fosforgehalten in de mest te verlagen, en wet en regelgeving. De economische toekomst van de veehouderijsector zal ook afhangen van de kosten van mestafzet. Er is dan ook behoefte aan goedkope mestverwerkingstechnieken en goede afzetmogelijkheden van dierlijke mestproducten. Dit kan door o.a. de energiewaarde te benutten en waardevolle nutriënten terug te winnen, waardoor ook een bijdrage wordt geleverd aan de energievoorziening en efficiënt wordt omgegaan met steeds schaarser wordende grondstoffen zoals fosfaat.

In de afgelopen decennia zijn er verschillende pogingen gedaan om mest te verwerken, maar zonder veel succes. Een van de belangrijkste redenen dat de markt voor geproduceerde mestproducten slecht verkend en weinig ontwikkeld was. Daarnaast waren er technische problemen en alternatieven met lagere kosten voorhanden, zoals plaatsing van dierlijke mest op bouwland en export naar aangrenzende landen. Echter, door het aanscherpen van de gebruiksnormen en de eisen ten aanzien van export van mestproducten, is het voordeel van deze alternatieven sterk verminderd. Er is dan ook een hernieuwde interesse in mestverwerking, ook al doordat er nieuwe en betere technieken ontwikkeld zijn en het besef dat fosfaatbronnen efficiënt gerecycled moeten worden en een economische waarde hebben.

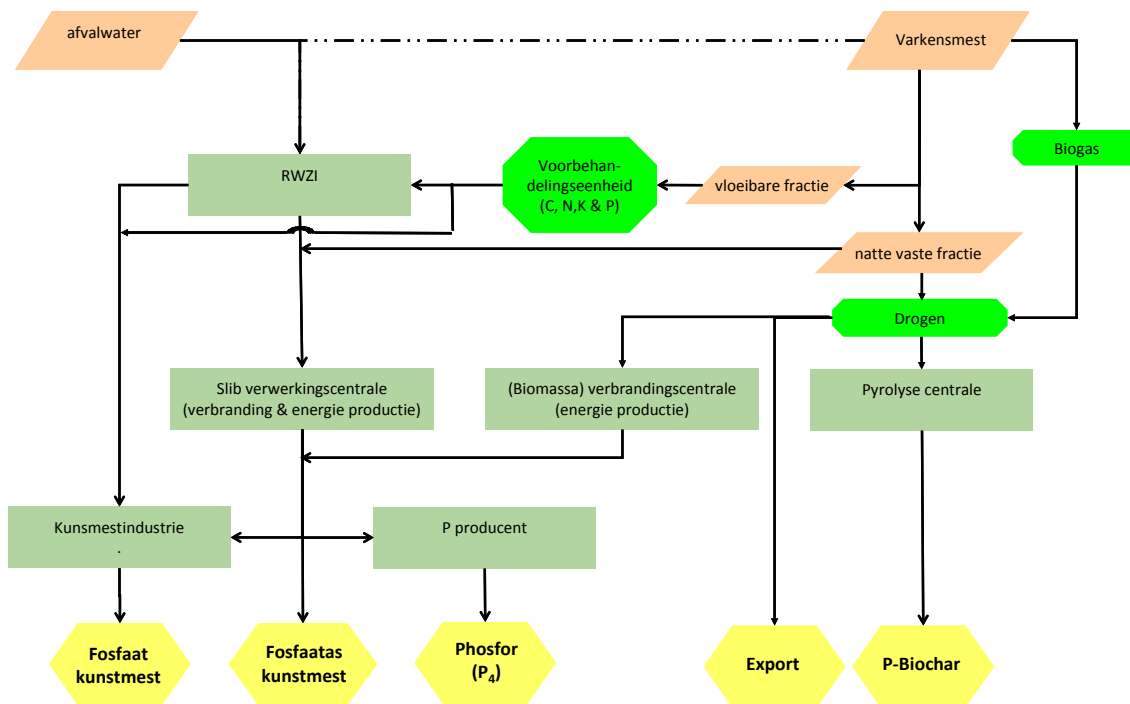
In dit rapport beschrijven we de resultaten van een verkennende studie naar de technische mogelijkheden en landbouweconomische perspectieven van fosforterugwinning uit dierlijke mest. De focus is op fosfaat omdat met name de fosfaatgebruiksnormen het Nederlandse mestoverschot bepalen. Verder is de focus op varkensmest omdat varkensmest geproduceerd wordt op bedrijven met weinig land, terwijl de afzet van varkensmest in het nadeel is ten opzichte van andere veel voorkomende mestsoorten zoals kippenmest (met een hoog droge stofgehalte) en rundveemest (dat geproduceerd wordt op bedrijven met grond waardoor deel van de mest op eigenland aangewend kan worden).

Allereerst hebben we een literatuur- en deskstudie uitgevoerd naar de ontwikkelingen en toekomstperspectieven van mestverwerking, waarbij ook de internationale ontwikkelingen is gekeken. Vooral op het gebied van afvalwaterzuivering zijn er grote stappen gemaakt vooral met betrekking tot de technieken om struviet (fosfaat-mineraal) terug te winnen. Ook technische vooruitgang is geboekt op het gebied van anaeroob (co-)vergisting, mestscheiding, (ultra-) filtratie en omgekeerde osmose van de dunne fractie van dierlijke mest, en drogen, composteren, pyrolyse en verbranding van de vaste fractie van dierlijke mest.

In de tweede plaats zijn gespreken gevoerd met instellingen en industrieën die afval verwerken en/of fosforproducten en meststoffen produceren. De bijeenkomsten richtten zich op de specificatie van ruwe grondstoffen die zij kunnen en willen verwerken, en de condities voor verdere samenwerking. Zowel SNB in Moerdijk, de grootste afval verbrander, ICL-Fertilizer te Amsterdam, de grootste fosfor kunstmest-industrie, als Themphos te Vlissingen, de grootste elementair fosfor producent in West-Europa, hebben hun interesse getoond om de bewerkte dikke fractie dierlijke mest als grondstof te gebruiken.

In de derde plaats zijn gesprekken gevoerd met instellingen die de dikke fractie uit dierlijke mest exporteren (voornamelijk gedroogde kippenmest). De export van vaste mest (met een hoog organische stof- en fosforgehalte) is over de afgelopen jaren sterk toegenomen. In 2009 werd een equivalent van 32 miljoen kg P_2O_5

geëxporteerd. De export van bewerkte varkensmest neemt ook toe. Echter, de export van deze producten is kwetsbaar en kan instorten indien dierziekten uitbreken. Deze kwetsbaarheid treedt niet op voor biochars die gevormd worden uit pyrolyse van de vaste fractie uit dierlijke mest. Echter, de markt voor biochars als bodemverbeteraar is nog weinig ontwikkeld in Europa. Buiten Europa (vooral Australië, VS en Canada) zijn biochars populair, omdat zij de bodemkwaliteit verbeteren. Biochars die uit dierlijke mest worden geproduceerd hebben een hoog fosfor gehalte dat een extra voordeel biedt indien deze wordt toegediend aan gronden met een lage fosfaattoestand. De fosfaatbeschikbaarheid van biochars hangt af van de pyrolyse temperatuur en tijdsduur. De fosfaatindustrie heeft ook interesse getoond voor P-biochars.



Figuur S1

Overzicht van de vermarktbare P-producten uit dierlijke mest en benodigde verwerkingstechnieken.

Tot slot zijn op basis van de verkregen informatie verschillende opties voor grootschalige fosfaat- en fosforterugwinning uit varkensmest beschreven en nader geanalyseerd. De mestverwerking-opties zijn gecategoriseerd in opties op bedrijfsschaal, regionale en nationale / centrale schaal. Een coherent schema van de geanalyseerde grootschalige toepassingen en de bijbehorende mestverwerkingstechnieken zijn in figuur S1 weergegeven. Elke optie is beschreven tezamen met de voor- en nadelen en de beperkingen. Hoewel het merendeel van de fosfaten in de dikke fractie zitten, mag de dunne fractie niet veronachtzaamd worden, ook al omdat de kosten voor afzet significant zijn als de dunne fractie niet dichtbij op het land aangewend kan worden.

Voor de opties zijn ook eenvoudige kostenvoordeel berekeningen uitgevoerd. Allereerst is de economische waarde van mest berekend gebaseerd op het nutriëntengehalte (N, P, K) en organische stof (energetische waarde). Andere eigenschappen gerelateerd aan mesttoediening, zoals het verbeteren van de bodemstructuur, bodembiodiversiteit, gehalten aan micronutriënten e.d. zijn niet meegenomen, omdat deze lastig te kwantificeren zijn, ondanks dat deze wel waarde voor een boer hebben. Gebaseerd op de marktprijzen voor N, P en K bronnen in 2010 en de energieprijzen, varieert de economische waarde van varkensmest tussen de 6 en 11 Euro per m³. Daarnaast zijn de economische kosten van mestverwerking geschat. De totale kosten voor

mestscheiding in een dunne en dikke fractie en drogen en transport van de dikke fractie naar het buitenland (export) of naar een centrale verwerking (voor verdere verwerking) bedraagt ongeveer 9 tot 14 Euro per m³ varkensmest (2 tot 3.5 Euro per kg P₂O₅ ofwel 5 tot 8 Euro per P). Het grote deel van de kosten heeft betrekking op het drogen (5 tot 8 Euro per m³) als geen externe warmte beschikbaar vrij beschikbaar is. Daarnaast zijn er kosten (transport en verwerking) die gemaakt moeten worden voor de afzet van de dunne fractie indien deze niet op nabij gelegen landbouwpercelen afgezet kan worden.

De kosten voor verbranden van de gedroogde fractie (60-90% droge stof) tot een P rijke as is ongeveer kostenneutraal of levert ruim 2 Euro per m³ varkensmest op door de energieproductie van de organische stof. Er wordt verondersteld dat de waarde van fosfaat-as gelijk is aan de waarde van fosfaaterts, namelijk ongeveer 0.85 Euro per m³ varkensmest. De kosten van verbranding van natte gescheiden mestkoek is ongeveer 10 Euro per m³ varkensmest en kan bij SNB worden uitgevoerd. De fosfaatrijke as na verbranding kan als grondstof gebruikt worden door de fosfor-industrieën Thermphos en ICL. Echter, deze industrieën willen eerst de P-rijke assen uit dierlijke mest testen voordat zij beslissen om het als grondstof daadwerkelijk te accepteren.

De netto kosten voor pyrolyse van gedroogde (60% DS) vaste varkensmest zijn ongeveer nul, aannemende dat de waarde van 1 kg of fosfor in biochar vijf maal hoger is (€ 4,25) dan de waarde van 1 kg of fosfor in as (€ 0,85). Anders zullen de kosten om biochar uit droge (60% DS) vaste varkensmest te produceren ruwweg 3-4 Euro per m³ varkensmest bedragen.

Naast de kosten voor mestscheiding, transport, verbranden of pyrolyse tot een droog P-grondstof of P-product uit dierlijke mest zijn er ook nog kosten die gerelateerd zijn aan de behandeling en afzet van de vloeibare fractie uit dierlijke mest. De goedkoopste route is om de dunne fractie op nabij gelegen landbouwgronden uit te rijden. Als dat niet mogelijk is dient de vloeibare fractie behandeld te worden voordat het op het oppervlaktewater geloosd kan worden, omdat de dunne fractie teveel organisch materiaal en nutriënten (N, P en K). Rioolwaterzuiveringsinstallaties berekenen de kosten voor zuivering aan de hand van het gehalte aan organisch materiaal en ammoniumgehalte van de vloeistof, omdat deze gehalten het chemische zuurstofverbruik (CZV) bepalen. De zuiveringskosten van de dunne fractie is ongeveer 30-50 Euro per m³ varkensmest (vloeibare fractie: gehalte organisch materiaal 7-10 kg/m³ en NH₃/NH₄ gehalte 3-6 kg/m³). Echter, de NH₃/NH₄ kan worden gestript van de dunne fractie door precipitatie tot struviet nadat fosforzuur is toegevoegd. Dit fosforzuur kan kosteloos geleverd worden door de kunstmestindustrie als het gevormde struviet terug wordt geleverd aan de kunstmestindustrie. De kosten van deze zuiveringstechniek bedragen ongeveer 10-14 Euro per m³ varkensmest.

De netto kosten voor de behandeling van varkensmest tot vermarktbaar producten worden geschat op 24-31 Euro per m³ varkensmest. Dit is ca. 6 tot 8 Euro per kg P₂O₅ of 14 tot 18 Euro per kg P. Ongeveer 50% van de kosten worden veroorzaakt door voorbehandeling van de dikke fractie (scheiden, drogen en transport) en de andere 50% voor de nabewerking van de dunne fractie (strippen van nutriënten).

De belangrijkste conclusies uit deze studie zijn:

1. De vaste fractie kan verwerkt worden tot (i) droge organische meststoffen, (ii) minerale P-meststoffen, (iii) elementair fosfor voor de food en non-food industries en (iv) biochar als bodemverbeteraar. Elk van deze producten en de route waarmee deze geproduceerd kunnen worden hebben voor- en nadelen, maar de netto economische kosten verschillen weinig.
2. Er is een risico dat de dunne fractie dierlijke mest is verwaarloosd, omdat deze fractie weinig waardevolle stoffen bevat. Echter, een integrale oplossing voor het mestoverschot is alleen mogelijk als zowel de dikke als de dunne fractie op een juiste wijze verwerkt en afgezet worden.

3. De vloeibare fractie kan verwerkt worden via (i) directe toediening aan landbouwgrond, (ii) via ultrafiltratie en omgekeerde osmose met directe toediening van de mineralen concentraten op landbouwgrond en directe toediening van de bijproducten op het oppervlaktewater, riool of landbouwgrond en (iii) via ultrafiltratie en precipitatie tot struviet of calciumfosfaat en verdere zuivering van het effluent op een rioolwater-zuiveringsinstallatie (RWZI).
4. De netto economische kosten van grootschalige verwerking van varkensmest zijn vergelijkbaar met of iets hoger dan de kosten van de afzet van varkensmest in 2009-2010.
5. De kosten voor verwerking van varkensmest worden voornamelijk bepaald door mechanische mestscheiding (2-5 Euro per m³ varkensmest), transport van de varkensmest fracties (6-8 Euro per m³ varkensmest), eventueel drogen van de vaste fractie (5-8 Euro per m³ varkensmest) en mogelijke behandeling van de dunne fractie (ongeveer 11-14 Euro per m³ varkensmest). De verwerking van de vloeibare fractie is noodzakelijk als directe toediening aan landbouwgrond geen optie is. Het economische voordeel van verbranden en energiewinning uit de gedroogde dikke fractie is ongeveer 1-2 Euro per m³ varkensmest. Indien niet-gedroogde mestkoek wordt verbrand is er geen kostenvoordeel en bedragen de kosten ca. 10 Euro per m³ varkensmest. De onzekerheden in de schattingen van de kosten zijn relatief groot als gevolg van variaties in condities in de praktijk.
6. Hoewel verschillende be- en verwerkingstechnieken goed ontwikkeld zijn, vereisen de verschillende opties voor verwerking van mest nog pilots op praktijkschaal om de praktische uitvoerbaarheid te testen en om de onzekerheden in de kostenschattingen te verminderen.
7. De organisatorische en institutionele aspecten gerelateerd aan grootschalige varkensmestverwerking zijn complex en vereisen grote organisatorische en ondernemende vaardigheden. De ondernemende vaardigheden zijn er, gelet op de ontwikkeling in de veehouderij, zoals ook nu weer uit het pilotproject mineralenconcentraten blijkt. De fosfor-industrieën tonen grote interesse in de as van verbrande mestkoek. Echter, het samenbrengen van de interesse van individuele boeren, industrieën en intermediairs (afval/mestverwerkingsbedrijven, transporteurs, leveranciers van restwarmte zoals centrales en industrieën) blijft een belangrijke uitdaging.

De belangrijkste aanbevelingen zijn:

1. De verschillende opties en routes voor mestverwerking zoals deze in deze studie zijn geïdentificeerd en samengevat in figuur S1 en tabel 9 zouden verder in detail bediscussieerd en vervolgens geprioriteerd moeten worden door de stakeholders.
2. De geprioriteerde opties en routes dienen getest te worden op pilotschaal om de praktische uitvoerbaarheid vast te stellen en de onzekerheid van de kostenschatting te verkleinen.
3. Mechanische scheiding van varkensmest in een vaste en vloeibare fractie is een goedkope no-regret bewerkingstrategie die de flexibiliteit voor verdere verwerking en afzet vergroot. Het wordt aanbevolen om de implementatie in de praktijk sterk te stimuleren, om verdere ervaring op te doen en zo de verdere toepassing te verbeteren en de kosten verder te verlagen.
4. Drogen van de dikke fractie varkensmest vereist externe warmte, die duur is indien geleverd wordt uit fossiele energie. Echter, wanneer restwarmte beschikbaar is bij warmtekrachtcentrales en industrieën, dan kunnen de kosten voor drogen sterk gereduceerd worden. Deze mogelijkheden dienen verder verkend te worden.
5. De verwerking en zuivering van de vloeibare fractie is relatief duur. Veruit de goedkoopste optie is directe toediening van de dunne fractie op nabij gelegen landbouwgrond. Aan de verwerking van de dunne fractie dient prioriteit gegeven te worden, ook door de mineralen N en K zo beter te benutten.
6. De gemiddelde kosten en de onzekerheid in de kostenschatting kunnen verminderd worden door gericht onderzoek, waar mogelijk samen met de stakeholders.

Executive summary

Forecasts suggest that the total amount of animal manure produced in the Netherlands by 2015 will exceed the total amount of animal manure that can be applied to agricultural land by an equivalent of 40-60 million kg P_2O_5 . The actual surplus amount of animal manure will depend on the economic development of the livestock sector, the success of animal feeding strategies to lower the amounts of nitrogen and phosphorus in the manure, and on environmental and legal restrictions. The economic prospects of the livestock sector also depend on the cost of manure transport and disposal. Evidently, there is a need for low-cost manure processing and disposal techniques and pathways. These must recover the energy and nutrients (mainly phosphorus and nitrogen) from the animal manure in environmentally sound manner, also because of the need to economize on phosphorus, energy and nitrogen.

Over the last decades several attempts were made to process animal manure, but without much success. A main reason for the lack of success was the fact that the market for processed manure was not well explored and developed. Furthermore, there were technical failures and there were 'low-cost' alternatives, i.e., the transport and disposal of manure on arable land elsewhere in the Netherlands and neighbouring countries. However, the 'low-cost' alternatives have diminished, due to the tightening of the application limits of manure application over time. As a result, there is renewed interest in manure processing, also because there are new techniques on the market and there is an increasing awareness of the need to economize on phosphorus resources worldwide.

Here, we report the results of an explorative study on technical opportunities and agro-economical perspectives of phosphorus recovery from animal manure. We focused on phosphorus, because the room for manure application on agricultural land in the Netherlands is restricted mainly by phosphorus (and nitrogen) application standards. Also, we focused on slurries from fattening pigs, because most of these slurries are produced on land-limited farms, while its disposal has a competitive disadvantage relative to for example poultry manure (which has a much higher dry matter content) and cattle slurry (which is mostly produced on farms with sufficient land for appropriated disposal).

Firstly, we made a literature and desk study to investigate the development and prospects of (new) techniques for the treatment of manure. Especially waste water treatment plants have made progress in the treatment of waste waters and the recovery of struvite (a phosphorus containing mineral) from it. Also technical progress has been made in the fields of anaerobic (co-)digestion, slurry separation techniques, (ultra-) filtration and reverse osmosis of the liquid fraction, and drying, composting, pyrolysis and incineration of the solid fractions.

Secondly, various companies that process wastes and/or produce phosphorus products and fertilizers were consulted. The consults related to specifications of the raw material they are able and willing to process, and to the conditions of further cooperation. Both, SNB in Moerdijk, the biggest waste incinerating plant, ICL in Amsterdam, the biggest phosphorus fertilizer industry, and Thermphos in Vlissingen, the biggest elemental phosphorus producing plant in the world, show interest in using solid pig manure as feed stock.

Thirdly, companies exporting solid manures (mainly dried poultry manure) have been consulted. The export of solid manure (with a relatively high organic matter and phosphorus content) has been increasing over the last years. In 2009, the equivalence of 32 million kg P_2O_5 was exported. The export of processed pig manure is also increasing. However, the export of these products is vulnerable and may collapse completely when animal diseases occur. This vulnerability is likely not the case for biochars, produced from the pyrolysis of solid

manure. However, the market for biochar as a soil amendment in Europe is still underdeveloped. Elsewhere (mainly Australia, US and Canada), biochars are becoming popular, because they may improve the soil quality. Biochars produced from animal manure have relatively high phosphorus content, which is beneficial when applied to low-phosphorus soils. However, the availability of the phosphorus depends on the pyrolysis temperature and duration. The phosphorus fertilizer industry has also shown interest in the use of biochar as feed stock.

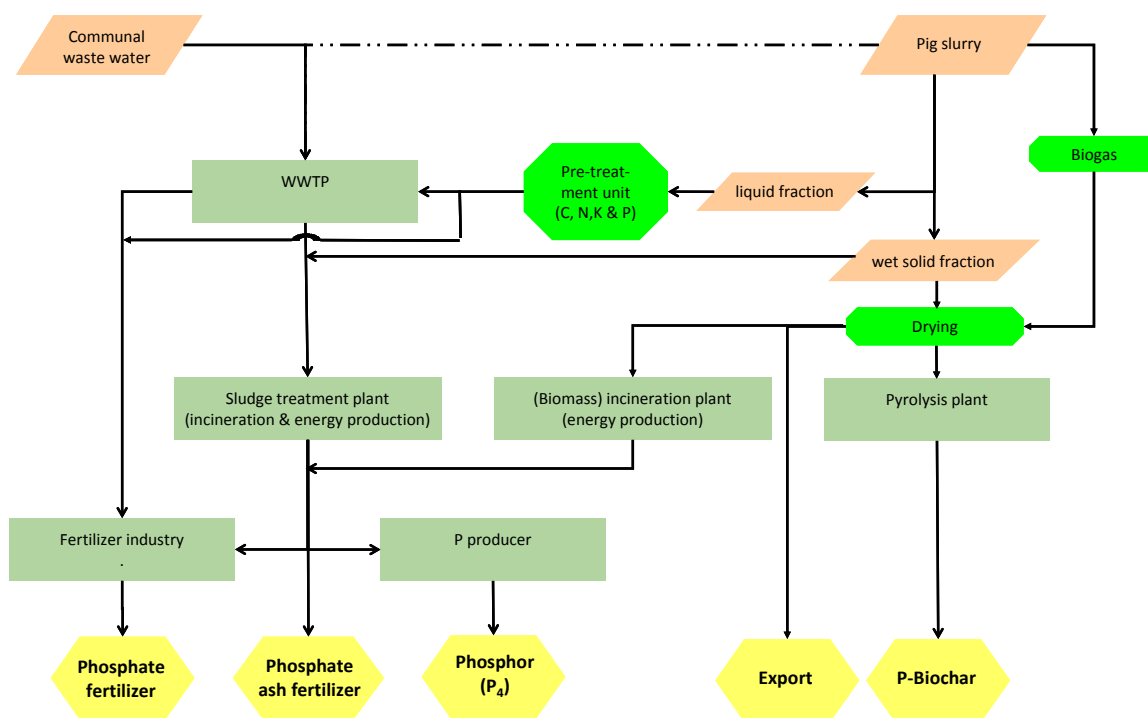


Figure S1

Overview of marketable P products from manure to existing markets and processing techniques needed

Finally, and based on all the collected information, various options for large-scale phosphorus recovery from pig slurries were described and assessed. The manure processing options were categorized in options for the farm scale, regional scale and national scale. A coherent scheme with all manure processing techniques and options is shown in Figure S1. Each option was described together with the (dis)advantages and limitations. Both, the solid and liquid fractions were considered. Although most of the phosphorus is in the solid fraction, the liquid fraction cannot be disregarded, also because the cost of disposal can be significant when application to nearby agricultural land is not feasible.

The options were also assessed economically, through simple cost-benefit calculations. Firstly, the economic value of manure was calculated based on the nutrients contained (N, P, K and organic matter, from an energetic point of view). Other possible soil fertility amending properties of manure applications, like improving soil structure, soil biodiversity, micro-nutrients, etc. were not taken into account, because these are hard to quantify, although there are various farmers that value these properties. Based on the 2010 market prices for N, P and K resources and energy prices, the economic value of pig slurry varies between 6 and 11 Euro per m³.

Secondly, the economic costs of manure processing were estimated. The total costs for separation of slurries into liquid and solid fractions, and for drying and transport of the solid fraction to abroad (export) or to a central plant (for further manure processing) are about 9 to 14 Euro per m³ pig slurry (2 to 3.5 Euro per kg P₂O₅ which equals to 5 to 8 Euro per P). Most of these cost are made for drying (5 to 8 Euro per m³) if no residual heat can be used for drying. Furthermore, there are costs (transport and treatment) if the liquid fractions cannot be applied on land from neighbouring farms.

The cost of incineration of the dried solid fraction (60-90% dry matter) of into a phosphorus-rich ash is about cost neutral or has a benefit of about 2 Euro per m³ pig slurry, mainly because the energy production out of the organic matter. Furthermore, it was assumed that the values of the phosphorus in ashes is similar to the value of phosphorus in rock phosphate, which equals 0.85 Euro per m³ pig slurry. The incineration of the wet cake solid fraction from separated pig slurry costs about 10 Euro per m³ pig slurry. It can be incinerated at the sludge waste water treatment plant of SNB. The phosphorus-rich ash of incineration plants may be used as feed stock by the phosphorus industries Thermphos and ICL. However, these industries need to test the phosphorus-rich ashes from incinerated pig manure before they can decide to accept it as a feed stock for their industries.

The net cost of pyrolysis of dried (60% DM) solid pig slurry fraction is likely zero, assuming that the value of 1 kg of phosphorus in biochar is 5 times higher (€ 4.25) than the value of 1 kg of phosphorus in ash (€ 0.85). Otherwise, the costs to produce biochar from dried (60% DM) solid pig slurry fraction will be about 3-4 Euro per m³ pig slurry.

Besides the cost to separate, transport, incinerate or pyrolysis the dried, solid fraction of pig slurry, there are also costs related to the treatment and disposal of the liquid fraction. The cheapest route is to apply the liquid fraction on agricultural land, if possible on the farmers own land, otherwise on land from neighbouring farms. If this is not possible, the liquid fraction has to be treated before disposal, because the liquid fraction contains too much organic material and nutrients (N, P and K) for direct discharge to surface waters. Waste water treatment plants calculate the costs for purification based on the organic matter content and ammonia content of the liquid solution, because these contents determine mainly the chemical oxygen demand (COD). The costs of treatment of the liquid fraction are about 30-50 Euro per m³ pig slurry (liquid fraction: organic matter content 7-10 kg/m³ and NH₃/NH₄ content 3-6 kg/m³). However, NH₃/NH₄ can be stripped from the liquid fraction by precipitation of struvite following the addition of phosphoric acid. This phosphoric acid may be supplied by the phosphorus fertilizer industry free of charge if the struvite is returned to the industry. The costs of purification of pre-treated (NH₃/NH₄ stripped) liquid fraction will be about 11-14 Euro per m³ pig slurry.

The overall net costs of the treatment of pig slurry into marketable products are estimated at 24-31 Euro per m³ pig slurry. This is about 6 to 8 Euro per kg P₂O₅ or 14 to 18 Euro per kg P. About 50% of the costs are caused by pre-treatment of the solid fraction (separation, drying and transport) and the other 50% for the pre-treatment of the liquid fraction (stripping of the nutrients).

The main conclusions of this study are:

1. The solid fraction can be treated further to produce either (i) dry organic fertilizers, (ii) mineral P fertilizers, (iii) elemental P for the food and feed industries, and (iv) biochar, to be used for soil amelioration. Each of these treatment pathways and resulting products has certain advantages and disadvantages, but the net economic costs seem not much different.
2. There is a risk that the liquid fraction is 'neglected', because it contains less valuable compounds. However, an integral solution for the surplus manure requires that the solid and liquid fractions are both disposed off in appropriate ways.

3. The liquid fraction can be disposed off either through (i) direct application to agricultural land, (ii) further treatment via ultra-filtration and reverse osmosis, with direct application of the mineral concentrates on agricultural land and the direct discharge of the by-product water to the surface waters, sewage system or nearby agricultural land, and (iii) further treatment via ultra-filtration and precipitation of struvite or calcium phosphates and further purification of the effluent at a Waste Water Treatment Plant (WWTP).
4. The net total economic costs of large-scale pig slurry treatment procedures similar or slightly higher than the costs of pig slurry disposal in 2009-2010.
5. The costs for pig slurry processing are mainly determined by separation (2-5 Euro per m³ pig slurry), the transport of the pig slurry fractions (6-8 Euro per m³ pig slurry), the optional drying of the solid fraction (5-8 Euro per m³ pig slurry) and the possible treatment of the liquid fraction (about 11-14 Euro per m³ pig slurry). The treatment of the liquid fraction is needed when direct application agricultural land is no option. The costs/benefits of incineration and energy recovery of dried manure cake are about 1-2 Euro per m³ pig slurry. In case (not dried) wet manure cake is incinerated, there are no cost/benefits and the costs are approx. 10 Euro per m³ pig slurry. The uncertainties in these estimates are relatively large, due to the large variations in possible conditions in practice.
6. Through the manure processing techniques seem well-developed and mature, various pig slurry treatment options require further testing at pilot scale, to test the practical feasibility and to decrease the uncertainty range of the cost estimates.
7. The organizational and institutional aspects related to large-scale pig slurry processing are complex and require great organizational and entrepreneurial skill. The entrepreneurial skill is there, as evidenced by the developments of many livestock farms, including those involved in the 'pilot project mineral concentrates'. The phosphorus industries also show great interest in accepting the ashes from incinerated manure cakes. Yet, bringing the interests of individual farmers, industries and intermediates (manure processing technology companies, transporters, waste heat supplying power plants and industries) together remains a challenge.

The main recommendations are:

1. The various treatment options and pathways identified in this study and summarized in Table 9 should be discussed in-depth and subsequently prioritized by stakeholders.
2. Prioritized manure treatment pathways and options should be tested at pilot scale to test the practical feasibility and to decrease the uncertainty range of the cost estimates.
3. Mechanical separation of pig slurry in solid and liquid fractions is a low-cost, no-regret treatment strategy that increases the flexibility of manure disposal. It is recommended to stimulate the implementation of this treatment in practice, also to gain further experience and to improve its performance and thereby to lower the costs.
4. Drying of the solid manure cakes requires external heat, which is costly when produced from fossil energy. However, when available at certain power plants and industries, the costs of drying are greatly reduced. These possibilities should be explored further.
5. The treatment and disposal of the liquid fraction is relatively costly. By far, the cheapest option is its direct disposal on nearby agricultural land. Priority must be given to this disposal pathway, also through increasing its comparative advantage relative to mineral fertilizer N and K.
6. The mean costs and the uncertainty ranges in the cost estimates can be decreased through targeted research, where possible together with stakeholders.

1 Introduction

1.1 Developments in animal production and phosphorus balances

For centuries, animal husbandry has been an important agricultural sector in the Netherlands (e.g. Bieleman, 2008). A very strong increase in especially milk, pig and poultry production occurred during the period 1960-1990. Thereafter, the production level more or less stabilized or even went down due to various agro-environmental policy constraints. The increase in animal production was made possible through various technological and market developments, including the import of large amounts of animal feed from abroad, via the harbour Rotterdam.

The increase in animal production was associated with an increase in the production of animal manure. As a result the amount of nutrients (especially nitrogen and phosphorus, but also micro nutrients like copper and zinc) applied via animal manure to agricultural land started to exceed the nutrient requirements of the growing crops. This has led to nutrient enrichment of agricultural soils, and to increased nutrient losses to atmosphere, groundwater and surface water.

In response to the increased awareness of the environmental consequences of intensive animal production, a series of agro-environmental policy measures (manure policy) have been implemented from 1985 onwards, including manure application limits. These application limits have been lowered step-wise during the last 25 years and as a consequence, the room for manure application on agricultural land has decreased. Animal farms with high animal density increasingly have to export animal manure to farms with 'room for manure application', i.e., farms without animals (arable and horticultural farms) or farms with low animal density. The economic cost for manure disposal has steadily increased during the last 25 years, because of the increasing volume and distance of manure transport. Also, farms accepting animal manure came in the position to ask for a fee for manure acceptance. A manure market was created, where the cost of manure disposal depended on the supply and demand of manure. And the value of manure became more negative over time. Evidently, the increasing cost of manure disposal threatens the economic profitability and competitiveness of intensive livestock farms.

Figure 1 gives an overview of the phosphorus input-output balance of agriculture in the Netherlands in the period 1970-2008. The phosphorus (P) surplus increased in the period 1970-1986, and decreased thereafter. The decrease of the P surplus is mainly caused by the decrease in the use of P fertilizer and the decrease in the amount of P in animal manure produced annually. The P content in the animal manure, especially pig and poultry manure decreased because of the decrease in the supplemental P in the feed, concomitant with additions of the enzyme phytase to increase the availability of the P in animal feed to monogastric animals. Also the output of P from agriculture increased, mainly through increases of the net export of animal manure to neighbouring countries.

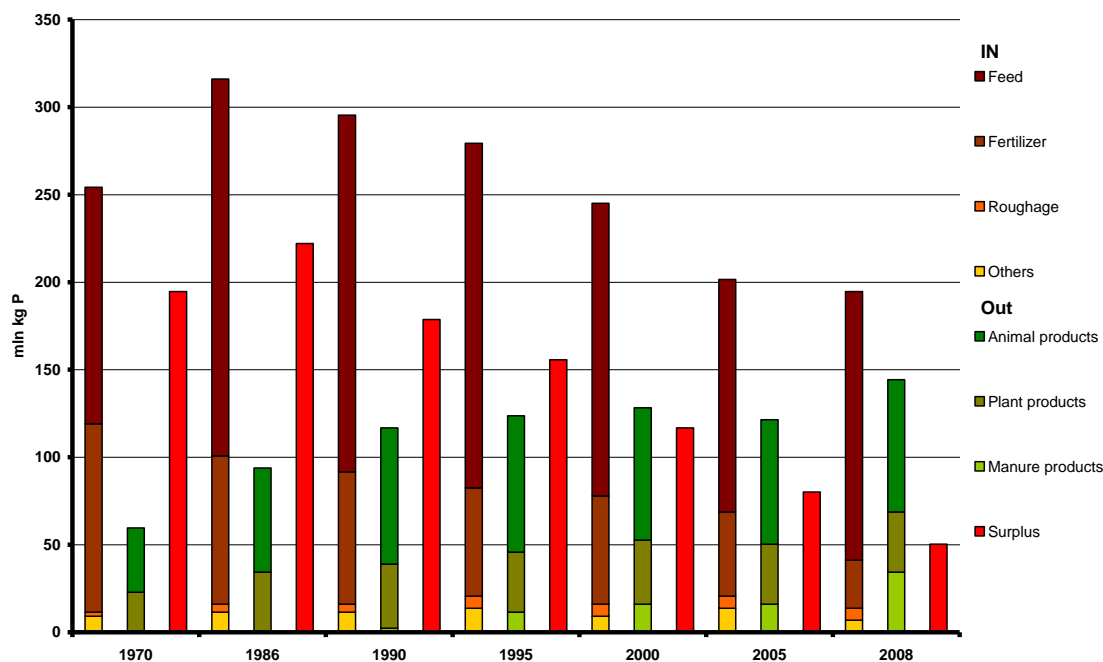


Figure 1

Annual input-output phosphorus balances for agriculture in the Netherlands for the period 1970-2008.

(Source: CBS <http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=37110&D1=a&D2=a&HD=101102-1100&HDR=G2&STB=T>).

Various attempts have been made during the last four decades to process animal manure into marketable products, to digest the manure anaerobically for the recovery of biogas and to treat the manure in such a way that it can be disposed off in a more easy way. Most of these previous attempts have not been successful. There have been technical failures, accidents and a poor market performance of manure products which have ceased most of the attempts. Most successful has been the low-tech drying and export of poultry manure. Recently, a power plant for electricity was opened in Moerdijk that has the possibility of incinerating dried poultry manure. All together, the equivalent of 20 to 35 million kg of P_2O_5 from manure has been exported during the last years (e.g. Luesink et al., 2008). Also, new techniques appear on the market, market prices for energy and fertilizers have gone up and the pressure on the manure market has also gone up. As a result, there is renewed interest in manure processing, especially for pig and cattle slurry.

There is growing acceptance that increasing amounts of manure phosphorus have to be recovered and exported, at current levels of animal production. From 2011, phosphorus application standards will depend on soil phosphorus status; P application standards will be relatively low when soil P status is relatively high, and vice versa. This policy measure will further decrease the room for manure application, as the mean soil P status is rather high. Forecasts suggest that the total amount of animal manure produced in the Netherlands by 2015 will exceed the total amount of animal manure that can be applied to agricultural land by an equivalent of 40-60 million kg P_2O_5 . The actual surplus amount of animal manure will depend on the economic development of the livestock sector, the success of animal feeding strategies to lower the amounts of nitrogen and phosphorus in the manure, and on environmental and legal restrictions. The economic prospects of the livestock sector also depend on the cost of manure transport and disposal. Evidently, there is a need for low-cost manure processing and disposal techniques and pathways. These must recover the energy and nutrients (mainly phosphorus and nitrogen) from the animal manure in environmentally sound manner, also because of the need to economize on phosphorus, energy and nitrogen.

1.2 Increasing awareness of limiting phosphorus resources

Most countries of the northern hemisphere have a soil P status that is rated 'sufficient' for crop production, as a result of past P fertilizer applications. In contrast, most countries of the southern hemisphere have a soil P status that is rated 'low' for crop production, as a result of long-term weathering and soil nutrient depletion. Especially in large parts of Africa, soils are very low in plant-available soil phosphorus, while the current low-input agriculture depletes the soil further.

The world production of P fertilizers and products is for about 80% of sedimentary marine origin (has relatively high contents of some heavy metal; especially Cd, U, Th) and some 17% is derived from igneous rocks and their weathering derivatives (has low heavy metal content, apatite type, mined mainly in Kola (Russia), Phalaborwa (South Africa), Araxa and Jacupiranga (Brasilia) and Siilinjärvi (Finland)). The remainder 3% comes from guano-type deposits (almost exhausted). (FAO, IFDC, 2008; USGS, 2009). More than 80% of the mined P is used for agricultural purposes (mainly for the production of P fertilizers and P additives in animal feed). Since the P rock reserves of a good quality (economically feasible) are limited, P scarcity is becoming an issue in the public discussion and gets more attention in scientific publications (Rosemarin, 2004; Cordell et al., 2009; Gilbert, 2009; Smit et al., 2009; Vitousek et al., 2009). Taking into account the expected increase of P use due to the population growth (from about 6 billion in 2000 to about 9 billion in 2050), the easily available P ores reserves of good quality will be consumed in a period of 50 to 130 years. This will increase up to 170-260 years in case the calculations are based on the reserved base (including the not yet feasible economical part, (Günther, 1997; Steen, 1998; Smit et al., 2009).

Hence, within two to three centuries, the now known P rock reserves will have been depleted and the P from these reserves will have been diffusely distributed over the world. Most of this P will have been accumulated in the top soil of agricultural land. This soil P is a potential source for eutrophication of surface waters due to erosion of soil material and leaching of soluble phosphorus. Especially high P soils are vulnerable to P losses via leaching and erosion. The risk of P losses from P enriched soils and the limited P rock reserves are the main reasons for P application limits in agriculture and the need for increased recycling of P from wastes and manure.

1.3 Innovations for lowering the phosphorus surplus

The former Minister of Agriculture, Gerda Verburg, has invited Wageningen UR to develop innovative strategies for a drastic lowering of the P surplus in agriculture, without compromising agricultural productivity. Six 'innovations' were proposed:

1. Reduce P inputs into agriculture via fertilizers and imported animal feed.
2. Make better use of the components in animal feed through bio refining.
3. Make use of the energy in manure (recovered via anaerobic digestion and incineration of manure cake) to improve further treatment of manure.
4. Separate manure into liquid and solid fractions for precision fertilization.
5. Produce NK fertilizers from the liquid fraction that can replace synthetic NK fertilizer.
6. Recover P from the solid fraction as a feed stock for P fertilizer industries.

Figure 2 shows the six 'innovations' in relation to the feed-manure-chain. Explorative desk studies were carried out for each of these proposed innovations in the period 2009-2010. The results of the 'P-recovery study' (sixth study) are reported in this report.

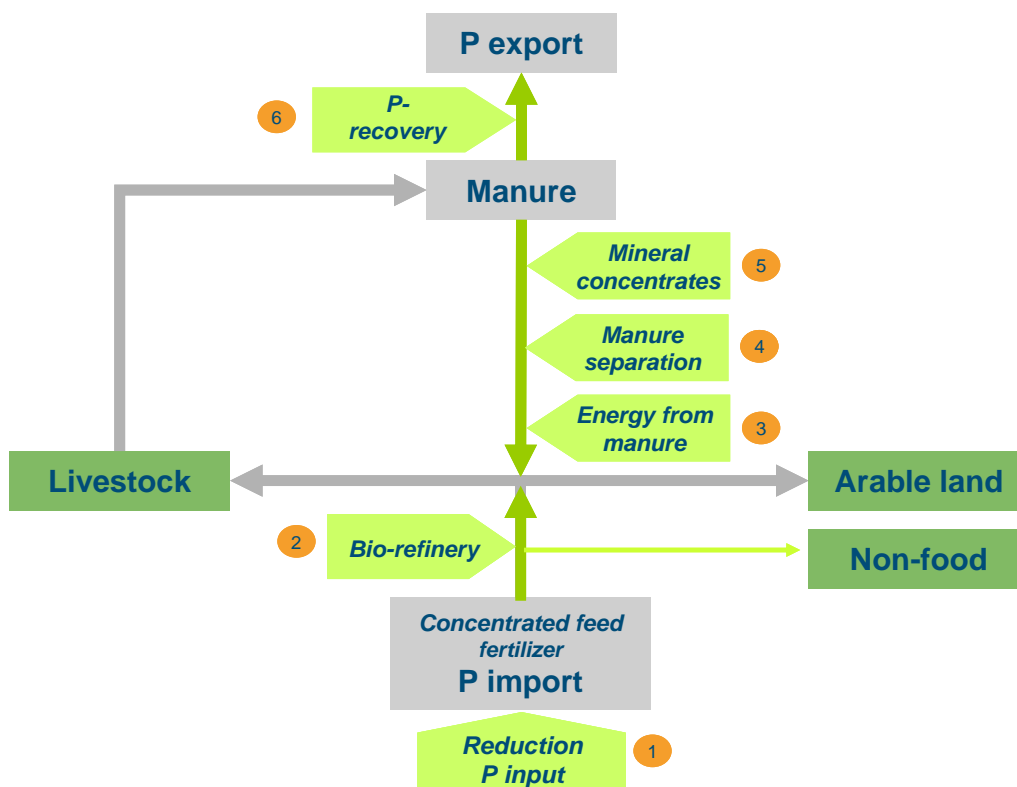


Figure 2

Scheme of the six proposed technical innovations to reduce the P surplus.

1.4 Objectives of the study

The main objectives of the study are:

- to identify technical options for the recovery of P from manure for use outside the Dutch agriculture;
- to explore the possibilities and constraints for the implementation of these technical options in practice;
- to explore the costs of the treatments in terms of investments costs and operational costs;
- to explore the advantages and disadvantages of the options;
- to give further recommendations for the most promising options.

1.5 Working program

The following activities have been carried out:

- Literature study.
- Visit International Conference Vancouver on Nutrient Recovery (Canada) including reporting.
- Evaluation of separation techniques.
- Consultations of stakeholders/contact persons: THERMPHOS, SNB, ICL-Fertilizer industries, ECN, STOWA, FIBRONED.
- Pre-evaluation of potential option for manure processing of the solid manure fraction.
- Pre-evaluation of potential option for manure processing of the liquid manure fraction (together with communal waste water).

- Experimental laboratory research regarding pyrolysis of dried solid cake of pigs manure in corporation with ECN; reported elsewhere (Ehlert et al., in prep.).
- Cost calculation of separation techniques.
- Identification of the costs of interesting manure treatment routes.
- Identification of future activities/recommendations.
- Meeting reports of meetings with industries.
- Dissemination.
- Reporting.

During the study frequently pre-evaluations were made and consequently new strategies were explored and discussed. Although the structure and original ideas have been changed, we have tried to bring together an overview of the techniques and the main potential options.

1.6 Lead

In Chapter 2 separation steps are described for the treatment of manure, especially in relation to recover P from manure. In Chapter 3 the development of P products for well known markets are described and discussed in cooperation with P consuming Dutch industries. In Chapter 4 an overall scheme is presented of the P recovery out of manure and the options are evaluated in terms of advantages and disadvantages. Furthermore the costs-benefits are estimated. Finally, the conclusions and recommendations are given (Chapter 5).

2 Manure treatment

There are many technical and technological options for the recovery and utilization of nutrients and energy from animal manure, but the main bottleneck of most options is its cost-effectiveness (e.g. Burton and Turner, 2003). Besides, many of these options are still in the development stage and need further research or practical application to gain experience.

The aim of this Chapter is to present a brief overview and assessment of treatment steps and treatment scenarios that might be useful for treating manure, especially regarding the recovery of phosphorus (P) from manure.

2.1 Standard composition of pig manure

For a useful discussion of the various options for manure treatment, it is necessary to consider the composition of the manure. Here, we focus on pig slurry for reasons mentioned in Chapter 1. The composition of pig slurry is presented in Table 1 (Bokhorst, 2000; Römkens and Rietra, 2008; Anonymous, 2008).

Table 1

Composition of pig slurry (concentration in kg m⁻³) (median value and min - max value between brackets).

Water ¹⁾	923	(989-872)
Dry solids ¹⁾	73	(11-128)
Organic matter ¹⁾		
N-Kjeldahl ¹⁾	6.3	(1.1-10.0)
– Ammonia (approx. 60% of N-Kjeldahl) ³⁾		
– Organic N (approx. 40% of N-Kjeldahl) ³⁾		
P (as P ₂ O ₅) ¹⁾	3.7	(0.6-6.2)
K (as K ₂ O) ²⁾	7.2 ¹⁾	
Ca (as CaO)	4 ¹⁾	
Mg (as MgO) ³⁾	1.8 ¹⁾	
Cl ⁻	2 ¹⁾	
S (as SO ₄)	2 ¹⁾	
pH	7	

¹⁾ Römkens and Rietra (2008).

²⁾ Bokhorst (2000).

³⁾ Anonymous (2008).

¹⁾ Standard deviation expected to be greater than 70%.

We can categorize the components of pig manure slurry in seven groups:

1. Water, by far the main component of pig slurry.
2. Organic compounds, mainly present as suspended or colloidal particles.
3. Nitrogen containing compounds, including ammonia/ammonium.
4. Phosphorous-containing compounds.
5. Major cations and anions, such as potassium, calcium, magnesium, sodium, chloride and sulphate.
6. Heavy metals such as Cu, Zn and Cd.
7. Weeds, pathogens, medicine residues and residues of pesticides, herbicides and fungicides.

Many of the components are distributed over the liquid phase, the suspended particles and the colloidal particles. As a result, many of the components cannot easily be recovered from the slurry. This holds especially also for phosphorus. Table 1 is used as a basis for further discussion and assessment of possible manure treatment routes relevant for P-recovery.

2.2 Treatment scenarios

Figure 2 provides an overview of the various possible treatment steps. The numbers in Figure 2 relate to the treatment steps discussed further below. A complete treatment process consists of a combination of individual treatment steps connected to each other in a logical way. Therefore in the discussion of the treatment scenarios for P recovery also attention has to be paid to treatment of the residual fractions. In the discussion of the various treatment steps not only references are made to literature dealing with manure treatment, but also to relevant literature dealing with more or less comparable wastes as manure such as Organic Municipal Solid Waste and Sewage Sludge and to literature dealing with industrial and agricultural wastewater streams that contain similar compounds as manure. General information can be found in Balmer (2004), Cornel and Schaum (2009), Durrant et al. (1999), Greaves et al. (1999), Lemmens et al. (2007), Melse et al. (2005), Montag et al. (2009), Rulkens (1990, 2008, 2010), Rulkens et al. (2002), Rulkens and Ten Have (1994).

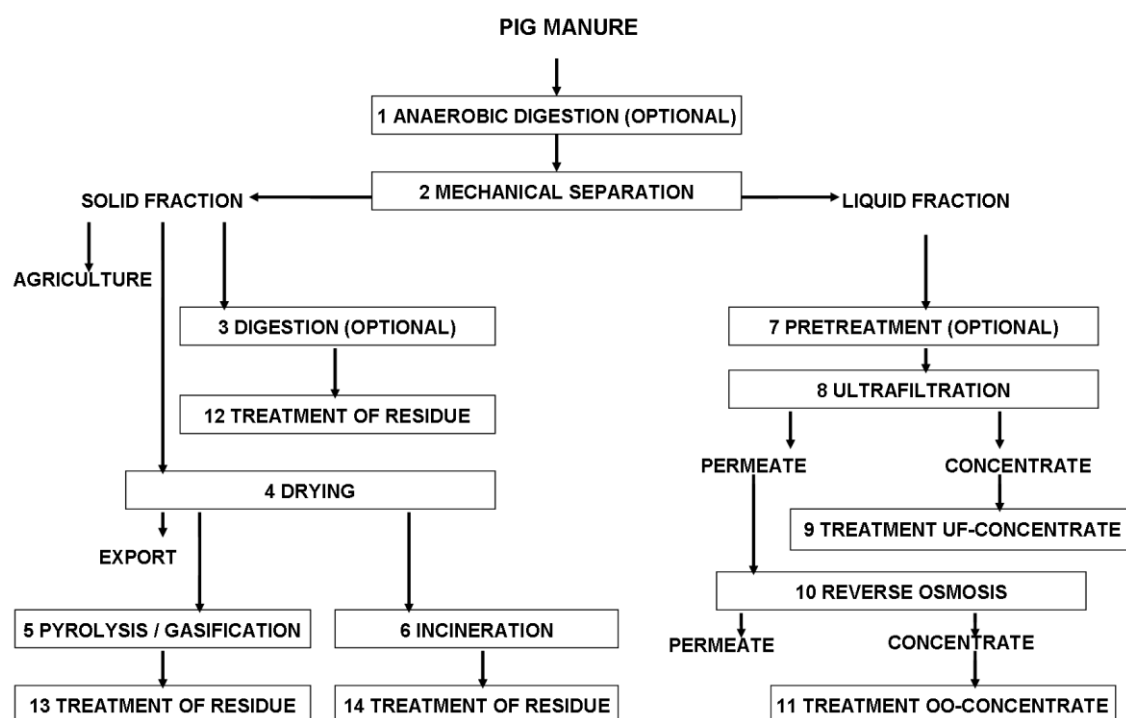


Figure 2

Processing steps to recover phosphate and phosphorus from manure.

2.3 Anaerobic digestion of pig slurry

The first step in a treatment scenario is often anaerobic digestion of the animal manure, with or without co-digestion of other organic wastes. Recovery of biogas from manure has financial benefits for the producer also because biogas production is subsidized. The biogas can be converted to electrical energy and heat. The heat can be used for further processing of manure (e.g. drying of manure).

Anaerobic digestion can be applied on whole slurry or on the solid fraction following the mechanical separation of the pig slurry in a solid fraction and a liquid fraction. Digestion of the solid fraction has the advantage that more energy is recovered per cubic meter of manure in the digester (because of the relatively high organic matter content of the solid fraction). The disadvantage is that the soluble organic compounds in the liquid fraction are not utilized, and hence still remain in the liquid fraction.

There exist several types of anaerobic reactor systems such as batch reactors, ideally mixed continuously flow slurry reactor systems and plug flow slurry reactor systems with partial recirculation of manure. Anaerobic digestion is possible at a temperature of 35 °C (mesophilic) or 55 / 60 °C (thermophilic). Compared to mesophilic digestion thermophilic digestion is faster, produces more biogas, is more sensitive to a high concentration of ammonia, the manure is more easily to dewater and the process requires more energy for heating the reactor. Thermophilic digestion however is less stable compared to mesophilic digestion.

Anaerobic digestion has effect on the further processing of the manure:

- The amount of biogas produced per m³ manure is about 20-30 m³ and can be increased with 50% up to 30-45 m³ with some pre-treatment steps (Timmerman and Rulkens, 2009). This biogas can be used subsequently for electric energy generation or for the heating and drying purposes (e.g., drying manure cakes).
- The organic matter content decreases; 20-25% is converted into biogas.
- Some of the organically bound nitrogen is mineralized and thereby increases the ammonia/ammonium content by about 15%.
- Some of the organically bound phosphorous is mineralized and thereby increases the concentration of inorganic phosphorus.
- The dewatering properties of the slurry increase, i.e., more components end up in the solid fraction following the mechanical separation of the slurry, and the drying of the solid fraction proceeds more rapidly.

Anaerobic digestion of manure can also be applied in combination with another organic waste and residues. In general this result in much more biogas. However the treatment of the resulting digestate is more complicated and all the digestate has to be considered as manure. Further, the concentrations of nutrients in the resulting digestate may be lower due to dilution, especially when the organic waste contains little nutrients. Experience with anaerobic dry digestion of the wet solid fraction of manure is very limited. However, a lot of practical experience, that might also be of interest for dry anaerobic digestion of wet solid manure is available with the anaerobic dry digestion (and also the wet anaerobic digestion) of the organic fraction of Municipal Solid Waste (Mes et al., 2007).

New developments in the anaerobic digestion of manure relate to thermal, physical, biological or chemical pre-treatment or post-treatment, to increase the production of biogas (Timmerman en Rulkens, 2009a). Pre-treatment can also be applied on the solid fraction obtained after a mechanical separation of the manure. Thermal treatment of this fraction at high temperature (150 °C) and pressure and at high pH aimed to increase the total production of biogas from the coarse fraction is under investigation. Another approach is the separation of the manure in a liquid phase and a solid phase, followed by anaerobic treatment of the liquid phase in a reactor with a short residence time and treatment of the solid phase in an ideally mixed slurry reactor with a long residence time. It might be useful and beneficial to have separate digestion of co-substrate and manure.

2.4 Mechanical separation of slurries into solid and liquid fractions

Many types of separation equipment and separation devices are available to separate the manure in a wet solid cake and a liquid fraction. As most important types of apparatus can be mentioned:

- Centrifuge
- Sieve belt press
- Filter press
- Screw press
- Rotating liquid sieve
- Vibration screen
- Sedimentation tank
- Dissolved air flotation installation
- Lamella separator based on sedimentation or dissolved air flotation
- Filtration by means of a straw bed

In almost all types of separation processes use of organic or inorganic coagulants and flocculants is in general a requirement in order to achieve a good separation between solid and liquid phases. Usual coagulants and flocculants are poly electrolytes, aluminium and iron sulphate, aluminium and iron chlorides, calcium oxide and calcium hydroxides, and also magnesium oxide and magnesium hydroxides. Use of calcium, magnesium and iron salts as coagulants results in the precipitation of dissolved phosphates and the concentration of the phosphates in the solid fraction. In case the recovered P is re-used in agriculture, Fe-containing coagulants/flocculants must be avoided. This holds to some extent also for Al-containing coagulants/flocculants. Use of coagulants and flocculants results in an increase of the costs of the mechanical separation process and has a strong effect on the further processing of the solid and liquid fraction

It is also possible to apply a two step mechanical separation technology. Such a process can save chemicals and can result in a sharper separation between a fraction that contains the suspended solids (in fact the solid fraction) and a fraction that contains most of the dissolved components originally in the manure.

A lot of experience is available regarding the use of mechanical separation techniques. The quality of the separation process can be characterized by three aspects (Schröder et al., 2009):

1. The rate of separation. A high separation rate results in a smaller equipment and therefore in general in lower costs. In all separation processes the focus is on a high rate of separation;
2. The efficiency of the separation with respect to the concentration of the suspended and colloidal particles in the solid phase. A high efficiency regarding the removal and concentration of suspended and colloidal particles means that almost all suspended and colloidal particles are concentrated in the solid phase and that the liquid phase contains dissolved components only. This type of separation is beneficial for the further processing of the liquid fraction. However a complete separation of the colloidal and suspended particles from the liquid phase mostly results in a relatively wet solid cake that has relatively high water content. This is a disadvantage if the further processing of this solid phase (solid fraction) is focused on drying, incineration, pyrolysis or gasification. In that case the removal of the water requires more energy.
3. The efficiency of the separation process with respect to the water content of the solid phase. A high efficiency means a separation of the manure in a solid fraction that contains low water content and a liquid fraction with high water content. This separation is beneficial for the further processing of the solid fraction (drying, sanitation, transport, direct use as a fertilizer in agriculture, incineration, gasification, and pyrolysis). However, this way of separation is not beneficial for the further treatment of the liquid phase because in this separation approach the liquid phase contains still a large amount of small particles.

2.5 Anaerobic digestion of manure cakes

As already mentioned anaerobic digestion of the mechanically separated solid manure fraction is also possible. It is only useful if no digestion process is applied on the manure slurry before the mechanical separation process. Following the anaerobic treatment step an aerobic composting treatment is necessary in general, in order to get a biologically stabile final product that easily can be stored, transported and handled.

A lot of experience exists with production of biogas from municipal waste. Several commercial available systems exist for the digestion of the solid wastes: Biocell process, Kompogas process, Dranco process, Valorga process (Mes et al., 2007). As yet, there is little experience with 'dry digestion' of the solid manure fraction of pig manure (Yadvika et al., 2004; Baere, 2003). In general 'dry digestions' systems are more complicated to operate than wet (slurry) digestion processes. The material to be treated has to be not sticky, needs to have a more or less porous open structure, and can be adequately transported through the reactor system.

An alternative process for anaerobic digestion of the solid fraction is composting. During composting, organic compounds are oxidized and released as CO₂ and water. The temperature during composting may increase to 65 / 70 °C and thereby a biologically stable and manageable product is obtained, pathogens and weeds are killed (to a certain percentage) and a substantial amount of water is evaporated. The compost can be used as soil amendment. Alternatively, the compost can be incinerated.

2.5.1 **Drying of the solid fraction**

Drying of the solid manure fraction results in a product with a lower weight and volume, that is biologically more stable and can be stored, transported and handled more easily. Drying is also needed for incineration of manure cakes. Relevant aspects in drying are (Timmerman and Rulkens, 2009b):

- a. Dryer/dryer performance
- b. Energy supply and energy use
- c. Drying conditions/process conditions
- d. Treatment of polluted drying gas

a. Most important types of dryers

- Direct dryer with direct contact between drying material and hot drying gases. In that respect rotating drum dryers, belt dryers and fluidized bed dryers can be mentioned. These dryers are characterized by a large volume of drying air to supply heat and to transport the evaporated water. The consequence is a large volumetric flow of polluted drying gas that has to be treated. This flow contains the evaporated water, ammonia and other odour components, and dust (dried manure) particles. Recovery of waste heat from the drying gas leaving the dryer is complex.
- Indirect dryers. In general rotating drum dryers, paddle dryers or fluidized bed dryers equipped with an internal heat exchanger. These dryers are characterized by a large volume of hot gases to supply the energy for the drying process via a heat exchanger or a heating liquid that supplies the heat via a heat exchanger and a small volume of the gas flow that transports the evaporated water, ammonia and other odour components, and small amounts of dust particles. The heating gas or heating liquid is not polluted. Compared with direct dryers the indirect dryers have the disadvantage that the dryer/drying equipment is more complicated but has the advantage that the volume of polluted gas that leaves the dryer and that has to be treated has a small volume and can therefore be treated in a more economic way. Also recovery of heat from this gas for reuse in the drying process is less complex and easier than in drying processes with direct dryers.
- Infrared dryers. In these dryers, in general belt dryers, the energy necessary for the drying process is supplied by infrared radiation from a gas fired infrared radiator or from an electrically heated infrared radiator. Compared to a standard direct dryer the infrared dryers are more expensive and also the energy supply from an electrically heated infrared dryer is more expensive. The advantage is that these types of dryers produce a relative low volume of polluted drying air.
- Dielectric dryers, based on heating by means of a high frequency electromagnetic field. The radio-frequency that is used in the drying process can vary and depends on the properties of the material that has to be dried. A disadvantage of a dielectric dryer is that electrical energy is necessary and the equipment is more expensive than conventional and indirect dryers. The advantage of a dielectric dryer is that the manure particles are directly heated inside and that the efficiency of heat transfer and the efficiency of energy use in the drying process is very high. Also the volume of the polluted gas flow that leaves the dryer and has to be treated is relatively small.
- Vacuum dryers which can operate at a lower temperature. The advantage is that the drying process can be operated at relative low temperatures and that it is easy to use low temperature waste heat. The dryer itself is more complicated.

- Steam dryers. In these dryers superheated steam is used as the drying gas. Part of the gas is recirculated over the drying system and part of the gas is treated. The treatment processes consist of a removal of pollutants and condensation of the water. Main advantage is that in general the energy efficiency of the drying process is relative high and that there is no risk for dust explosions because of the absence of oxygen. Treatment of the gas leaving the dryer and recovery of heat from this gas for reuse in the drying system is simpler.
- Drying processes according to the Carver Greenfield drying principle (Rulkens and Ten Have (1994)). In this drying process the mechanically dewatered solid manure fraction is mixed up with a non-toxic, bio-degradable light iso-paraffinic carrier liquid with a boiling point above that of water, and a very low solubility in water. The carrier fluid/wet solid manure mixture is fed to a boiler or a multi-effect evaporator for evaporation of the water. After the evaporation of the water the mixture of carrier fluid and dried manure particles is separated in a centrifuge. The carrier fluid is reused in the drying process. A stripping process can be applied to remove residual carrier liquid from the dried manure particles. This carrier fluid is also reused in the drying process. The advantage of this system is that its energy efficiency is very high because the principle of a multi-effect evaporator can be applied.

b. Energy supply

An important aspect in drying is the energy supply and the net energy use of the drying process. Energy supply is possible by:

- Hot gases of an incinerator;
- Hot infrared radiation from a gas fired heated radiation device or an electrically heated radiation device;
- Hot superheated steam;
- Electrical energy in case of microwave dryers;
- Low temperature heat from the ventilation air of pig houses;
- Waste heat from an incineration plant for organic wastes or from an electrical power plant.

c. Drying process conditions

- The volume flow of the drying air necessary for the drying process depends on the amount of water that has to be removed and on the temperature.
- If the focus of the drying process is also to remove ammonia, then in general a pH increase of the solid manure by addition of CaO or Ca(OH)₂ has to be applied. This can be achieved already in the coagulation/flocculation process of the mechanical dewatering step of the slurry manure. In case ammonia evaporates from the solid manure cake during the drying process this ammonia has to be recovered from the drying gases.
- If the focus of the drying process is to retain the ammonia in the dried product as much as possible, then acidification with, for example sulphuric acid, can be applied.
- Due to the formation of dust particles in combination with the presence of oxygen in the drying gas risks of dust explosions might exist.
- Supply of wet dewatered manure solid cake to the dryer requires in general special equipment and/or a recycling of a part of the dried product with the wet product that enters the dryer.

d. Treatment of polluted drying air

The air (off-gases) leaving the dryer contains water vapour, ammonia, other organic pollutants and dust particles. This air has to be treated, especially regarding ammonia and other components and dust particles. For an efficient treatment also the water vapour has to be removed from this air stream. Besides it can be interesting to consider the possibilities to recover energy from this airflow that can be reused in the drying process (maybe by the use of heat pumps):

- Removal of dust particles (manure particles) can be obtained by a cyclone, an electrostatic filter or a fabric filter. Maybe it is useful to apply a simple dust removal device before entering the heat exchanger.

- Removal of water can be applied by condensation in an air cooled or water cooled heat exchanger. The condensate might be slightly polluted with ammonia, odour components and materials present in the dust particles.
- The off gases leaving the heat exchanger have to be treated in an acid scrubber (where ammonia is absorbed in, for example, sulphuric acid) and/or in a bio filter or bio scrubber where the other odour components are removed by microbiological degradation.

In general standard equipment can be applied. With certain types of dryers there exists a lot of experience.

Two innovative approaches, still in the development phase for manure treatment, might be possible to recover energy from the polluted drying air for application in the dryer:

- Use of a heat pump;
- Use of zeolites as an adsorbent for water and storage for energy that might be reused.

It has to be remarked that the specific conditions how to treat the polluted air leaving the dryer strongly depend on the type of dryer, the drying conditions and the composition of the mechanically dewatered solid manure cake. This also holds for the costs of the treatment process.

2.5.2 Pyrolysis and gasification of manure

Pyrolysis is a process in which organic matter is indirectly heated to a temperature of 300-550 °C in the absence of oxygen (Bridgwater, 2004; Bridle and Pritchard, 2004). Because most organic substances are instable at these temperatures, thermal cracking and condensation reactions take place. The organic matter is then converted into a char (charcoal), pyrolysis oil, water phase, and a gas phase (syngas). The fraction of carbon, originally present in the manure cake that remains in the char of the pyrolysis process is in the order of 60-70%, dependent on the type of biomass or bio waste and the applied process conditions in the pyrolysis process. It can be expected that also the heavy metals present in the manure cake are more or less completely concentrated in the char. The gas phase consists of water vapour, CO₂ and combustible gases such as CH₄, H₂, and CO. The pyrolytic oil contains low molecular organic components such as organic acids and aromatics. Dependent on the type of organic waste also components such as NH₃, H₂S, COS and HCN can be present in the gas phase. Pyrolysis can be used to convert biomass and organic wastes including manure cakes into syngas and safely disposable substances. The gas that is produced in the pyrolysis process can be used for the production of electrical energy.

Gasification involves the breakdown of organic matter in an ash (char) and in combustible gases at temperatures usually about 800-1000 °C in an atmosphere with a reduced amount of oxygen. The fraction of the original amount of carbon present in the manure cake that remains in the char is relatively low, in the order of 10%. The gas phase obtained in the gasification process contains more or less similar components as in the pyrolysis process. Because a substantial part of the organic components is oxidized, the gas phase obtained in the gasification process contains a higher fraction of CO₂ than in the process of pyrolysis.

Pyrolysis and gasification have potential advantages compared to incineration. A main advantage is that the conversion of the combustible gases of both systems into electrical power can be achieved more efficiently. Further, the fraction of nutrients recovered in biochar is larger than in ashes, while the plant-availability of the nutrients tends to be higher in biochar than in ashes, especially in the case of phosphorus.

For treatment of manure cake aimed at the recovery phosphorus, pyrolysis seems more attractive than gasification, because of the lower temperature. At temperatures of 600-1000 °C phosphorus may become occluded by silicates, and iron and aluminium oxides, making the phosphorus unavailable to plant roots. Because manure cake contains also relatively large amounts of N and S it can be expected that the gases obtained in a pyrolysis and gasification process will contain HCN and H₂S. Different types of pyrolysis and gasification reactors are available. As yet, there is no experience with the pyrolysis and gasification of solid manure in practice. However, information is available regarding gasification (and to a much lesser extent of pyrolysis) of biomass, such as wood and organic residues from the food industry. Experiments with the pyrolysis of manure cakes have been reported by Ehlert et al. (2011).

2.5.3 Incineration of wet or dried manure cake

Manure cakes can be incinerated in combination with the production of electricity and heat. The process is more or less similar to that of the incineration of sewage sludge applied by the sewage sludge treatment plant in Moerdijk (Slibverwerkingsbedrijf Noord-Brabant; SNB). It can also be compared to the existing processes for incineration and production of energy from poultry manure or biomass at the biomass incineration plant in Moerdijk (Biomassa Centrale; BMC) or Fribroned in Apeldoorn. Incineration of biomass and wastes yields ashes, which contain all the phosphorus (mainly as calcium phosphates). Basically this phosphate can be used in a beneficial way by industries that produce elemental P and fertilizer P. It is expected that the major part of the heavy metals present in the manure cake is concentrated in the ash. In general the treatment of the exhaust gases of the incineration process can occur accordingly to standard treatment technologies. It is possible to recover waste heat from the exhaust gases of an incineration process for manure cake and to use this energy for drying wet manure cake

In case of manure incineration with subsequent P recovery, special attention has to be paid to:

- Prevention of emission of dioxin and furans with the exhaust gases of the incineration process;
- The maximal allowable / tolerable contents of potassium, silicon dioxide and iron and aluminium oxides in the manure cake;
- The maximum allowable / total amounts of Cu and Zn, or other heavy metals, in the manure cake. For example, the maximal allowable content of Cu is 500 mg/kg ash and for Zn 1000 mg/kg ash for elemental P recovery. Selective removal of heavy metals from the ash is possible by means of a (wet) extraction process, thermal volatilization.

Furthermore it has to be remarked:

- Incineration is feasible only at large scale;
- The high investment costs and long preparation procedures require long-term commitments and contracts;
- Co-incineration in existing incineration plants for sewage sludge (SNB) or for chicken manure might be economically more attractive in the short term, but will depend on the quality of the ashes and hence the problems for further processing these ashes.

2.5.4 Pre-treatment of the liquid fraction

The liquid fraction, obtained after mechanical separation, contains soluble components and some colloidal and suspended particles. These colloidal and suspended particles contain insoluble organic compounds and insoluble inorganic compounds such as phosphate or phosphorous containing components, calcium and magnesium precipitates. This is especially the case when the efficiency of the mechanical separation is low.

Pre-treatment of the liquid fraction aims at the precipitation of phosphorous and the removal of this precipitate together with the other colloidal and suspended particles. This precipitation process can be achieved by addition of Ca(OH)_2 to increase the pH and to precipitate PO_4 as calcium phosphates. An additional advantage of the addition of Ca(OH)_2 may be that in this way also NH_3 can be removed by stripping. Instead of a sedimentation process it is also possible to apply a flotation process or a filtration process. An efficient performance of a flotation process, a sedimentation process or a filtration process requires the use of inorganic or organic coagulants and flocculants. The obtained precipitate can be added to the manure cake.

It is of course also possible to remove especially colloidal and suspended particles but not the phosphate. This might be useful if the aim is to produce struvite from the co-precipitation of NH_4 , K, Mg and PO_4 . Formation of struvite requires the presence of sufficient amounts of PO_4 . In this case a careful selection of coagulants and flocculants in the mechanical dewatering process and in the pre-treatment process is required. However, the solubility of struvite in water is relatively high. That means that there is still a relatively high amount of ammonia and phosphate dissolved in the liquid phase. Furthermore the molecular concentrations of ammonia and phosphate in the liquid phase are in general not equimolar as in struvite.

2.5.5 Ultra filtration of the liquid fraction

In this process a semi-permeable membrane is used that is permeable for water and low molecular soluble compounds and that is not permeable for particles and soluble macromolecules. The water is forced through the membrane by application of a relatively low pressure over the membrane. The aim of the ultra filtration process is to remove and concentrate residual colloidal and suspended particles and soluble macromolecules from the liquid phase. Dependent on the process conditions applied in the mechanical dewatering process and the pre-treatment process, especially regarding the used coagulants and flocculants and the pH, the liquid phase obtained after the pre-treatment process can also contain still relatively large amounts of dissolved phosphate. This phosphate can be precipitated at high pH with calcium oxide, calcium hydroxide or magnesium oxide. If the pH of the permeate of the ultra filtration process is high enough it is possible to remove ammonia by stripping and absorption of the ammonia from the gas phase in a concentrated solution of an inorganic acid or it can be recovered as a concentrated solution of ammonia in water.

2.5.6 Treatment of the concentrate obtained with ultra filtration

The concentrate obtained with ultra filtration can be added to the mechanically dewatered cake. Another possibility is to add the precipitate to the manure before the mechanical dewatering process. The feasibility of the latter option depends on the fraction of soluble macromolecules present in the concentrate. These insoluble macromolecules cannot be separated from the liquid phase by a mechanical dewatering process.

2.5.7 Reverse osmosis of the liquid fraction

Reverse osmosis has the advantage of recovering NH_3 , PO_4 , K and other cations and anions in concentrates, while the permeate can be discharged to surface waters or can be used as irrigation and cleaning water. In reverse osmosis, a semi-permeable membrane is used that is permeable for water and that has a low permeability for all types of soluble compounds. The water is forced through the membrane by application of a high pressure. The treatment process results in a relatively large permeate flow consisting of water with a low concentration of soluble compounds and a relatively small concentrate flow in which most of the soluble compounds such as NH_3 , K, PO_4 and other soluble minerals and particles are concentrated.

2.5.8 Treatment of the mineral concentrates from reverse osmosis

Several treatment processes are available to further treat the concentrate from reverse osmosis. Recovery of PO_4 from the concentrate is possible by precipitation of struvite ($\text{MgKNH}_4\text{PO}_4$) (Doyle and Parsons, 2002; Lehmkuhl, 1990; Moerman et al., 2009; Sanchez et al., 2009; Schulze-Rettmer, 1991). The first step in the precipitation process is to increase the pH to a level above 9 and if there is not enough soluble Mg present in the concentrate to add MgO or MgCl_2 to the concentrate. Precipitation/crystallization of PO_4 as calcium phosphate or calcium hydroxyl phosphate is possible by adding Ca(OH)_2 to the concentrate and to increase the pH. This process can be followed by stripping of the ammonia with air in combination with absorption of ammonia from the stripping gas in an inorganic acid or in water (Altinbas et al., 2002). Ammonia in a water phase can be concentrated by means of a distillation process. Recovery of ammonia from the concentrate can also occur by struvite precipitation. Because of the relatively low molecular concentration of PO_4 compared to the molecular concentration of ammonia, PO_4 has to be added to the concentrate in order to remove all the ammonia as struvite. Because of the high costs of PO_4 this approach is economically not feasible. A solution for this problem is to evaporate ammonia from the struvite precipitate by heating it and to recover magnesium hydrogen phosphate for reuse. This saves phosphate and magnesium salts. The evaporated ammonia can be absorbed in water or in a concentrated aqueous solution of a mineral acid. Another possibility is to release ammonia from struvite by acid treatment of the wet or dry precipitate. Also in this case magnesium hydrogen phosphate can be reused in the precipitation process. Recovery of K is also possible by means of the precipitation of potassium struvite, KMgPO_4 (Schuiling and Andrade, 1999). Formation of KMgPO_4 occurs at high pH if the concentration of NH_3 is low and K, Mg and PO_4 are present in equimolecular amounts. Recovery of K from potassium struvite is possible.

It has to be remarked that regarding the application of membranes to recover separately ammonia, potassium and phosphate from the liquid phase several modifications exist. Besides ultra filtration and reverse osmosis also microfiltration, nanofiltration, electrodialysis and transmembrane chemisorption can be considered as possible membrane processes to achieve this aim.

2.5.9 Treatment of the residue of dry digestion

Processing of the residue of the dry digestion process (anaerobic composting) can occur according to the following:

- Aerobic treatment, to stabilize the organic matter and to remove additionally some water from the anaerobic compost;
- Mechanical drying of the anaerobic compost, but prevention of stench is needed;
- Incineration, gasification or pyrolysis of compost or mechanically dried residue of the anaerobic dry digestion process.

2.5.10 Treatment of biochar

The main purpose of a biochar obtained from the pyrolysis of the wet or dried solid manure cake is its use as a soil amendment or fertilizer. If this will not be possible then the char can be incinerated for the production of energy. The ash from such an incineration process is virtually comparable with the ash obtained in a direct incineration process of wet or dried solid manure fraction.

2.5.11 Treatment of ashes from manure incineration

Incineration of sewage sludge and manure results in ashes that contains phosphate, potassium, heavy metals and Al and Si containing compounds and possibly also some heavy metals such as Cu, Zn, and Cd. It is possible to use these ashes as a substitute for phosphate rock in the industrial production of phosphorous or to use as raw material for phosphate fertilizers. If the ash contains too high concentrations of heavy metals, such as Cd, Cu and Zn, then these heavy metals may be removed by thermo-chemical treatment, following the addition of magnesium chloride or potassium chloride (Hermann, 2009). By heating this mixture to temperatures above 1000 °C the heavy metals evaporate as heavy metal chlorides and are removed as heavy metal waste from the gas phase. In case the ashes are used by the fertilizer industry there are also specific requirements regarding the maximum amount of heavy metals in the ash. It is probably also possible to use the ash directly as a fertilizer, although availability of the phosphate to plant may be low. Recovery of phosphate from the ash is expected also to be possible by means of an extraction process with an inorganic acid such as sulphuric acid (Schaum et al., 2009). In such an extraction process it is also possible to include a selective removal process for heavy metals such as Zn and Cu.

3 Development of P products for well known markets

This chapter describes five plausible scenarios for the production of phosphorus-rich products from manure:

1. Production of elemental phosphorus (P) from the solid fraction of manure;
2. Production of P-rich fertilizer from the solid fraction of manure;
3. Production of P-rich biochar from the solid fraction of manure;
4. Production of calcium phosphate from the liquid fraction of manure;
5. Production of struvite from the liquid fraction of manure.

The presumption is that these P-rich products can be exported and marketed to other countries by companies and industries (e.g., fertilizer industries and P producer) in a competitive way. When exported, the P output from agriculture in the Netherlands is increased and hence, the P surplus decreased.

The first treatment scenario provides the opportunity to remove large amounts of P from agriculture, because the resulting elemental phosphorus can be used by various industries (e.g. detergent and food industries). The second treatment scenario also has a large potential for removing P from agriculture through the production of common P fertilizers, which are used in basically all countries of the world. With respect to third scenario, additional marketing research is necessary to further explore the market of such products. At present, there is a large interest in biochar, because of its inferred soil quality amending properties, but the size and 'sustainability' of its market are not known in quantitative sense. The last two of the aforementioned scenarios deal with the recovery of P from the liquid fraction of manure, which has a relative low P content and high NH_3 and K contents. The scenarios for the recovery of P from the solid fraction (scenarios 1-3) and those for the liquid fraction (scenarios 4 and 5) combined provide an integral solution for the treatment of excess animal manure.

In the following sections a short description of each treatment scenario is given, while taking the views of the stakeholders into account.

3.1 Elemental P production

Thermphos is the largest elemental phosphorus producing industry in Western Europe. It is located near Vlissingen, in the southwest of the Netherlands. Thermphos uses approximately 700,000 ton phosphate ore from rock phosphate mines. The policy of Thermphos is to substitute part or all of the phosphate ores by P rich resources from residues, such as ashes from the incineration of biomass and sewage sludge.

Currently, Thermphos uses phosphate rock (13 -1 7.5% P weight mass; 30-40% P_2O_5) as base material to produce P. The production process is described in detail by Schipper et al. (2007). By means of wet granulation and sintering, pellets of 1-2 cm of phosphate rock are made. The rock pellets are mixed with cokes (used as reducing agent) and gravel (SiO_2 , for slag formation). The mixture is fed into a furnace and heated by electric resistance to 1500 °C. At this temperature phosphate is reduced, vaporized and leaves the furnace together with CO and some dust. An electrostatic precipitator is used to remove the dust which is recycled into the process. CO is used as fuel in the sintering stage and other processes. By lowering the temperature of the gases via two towers (warm tower and cold tower), the P_4 is condensed and collected after

filtration. Two forms of slag are formed in the furnace, a ferrophosphorus slag which is used as a steel additive and a slag that consists of CaSiO_3 and some metal oxides. This slag is used for road construction. Figure 3 shows the phosphorus production process as described by Schipper et al., 2007.

At present, SNB and Thermphos explore the feasibility of recovering elemental P from ashes derived from the incineration of sewage sludge. Thermphos does accept only ashes with a low iron (Fe) content, because ashes with a high Fe content complicate the recovery of P from ashes. Ashes derived from the incineration of manure cake have a relatively low Fe content. In theory, co-incineration of low-Fe manure with sewage sludge could technically increase the volumes of ashes. A possible dilution of Fe-rich sewage with low-Fe manure is not preferred by Thermphos. SNB also investigates alternative routes for the disposal of ashes; they consider the recovery of P fertilizers from the ashes as a possibility. For such routes the co-incineration of manure with sewage sludge could also be an option.

The most important conditions of the material as used for P recovery by Thermphos are (see also Roeleveld et al., 2004):

- Phosphate content: $> 200 \text{ g P}_2\text{O}_5 \text{ kg}^{-1}$ dry matter. In general the P_2O_5 content should be higher than 18% on dry matter bases, depending however on the other components of the material;
- No organic carbon present;
- Water content less than 5% because of the mixing and milling process;
- Iron content should be as low as possible, because Fe will be reduced (increased energy and coke usage) and more ferrophosphorus slag will be formed. Therefore in general a Fe/P molar ratio below 0.2 is needed;
- Ammonium content as low as possible, because emissions of NH_3 will cause a serious gas scrubbing problem during the sintering stage. As a consequence Thermphos cannot use struvite (ammonium magnesium phosphate or potassium magnesium phosphate) as raw material;
- Copper content should be as low as possible, because Cu reduces the quality of the ferrophosphorus to be used as steel additive. Maximum allowable copper content depends strongly on the main composition of the material, such as Fe and P content.
- Volatile metals (zinc, lead, cadmium and tin) should also be as low as possible because they are associated with the dust which is recycled in to the process. So they will build up in the process system. Maximal allowable amounts of these heavy metals are in the same order as the maximum allowable amount of Cu.

In order to fulfil these conditions, the organic P resources have to be incinerated first to generate P-rich ashes. This can be done at the sewage sludge incinerator of SNB. At this moment all the capacity of the installation is used for the incineration of sewage sludge, but in the near future free capacity could be generated by process improvements and reduction of sewage sludge volumes. The main reason is that the amount of sewage sludge produced at municipal WWTP's will reduce in future because of the fact that more and more digestion units are built at WWTP's. The sewage sludge taken in by SNB has a dry matter content of 23% (77% water) and organic content of 62% (mass dry weight). The costs to process this sludge in the incinerator is about 300 Euro per ton dry matter (approx. 75 Euro per ton wet sludge).

If the remaining capacity can be used for incineration of manure cake a price of 10-15 Euro per ton wet manure cake seems to be possible. The costs depend on the composition of the wet manure cake: dry-matter content, P concentration, organic matter content and S and Fe content. With the current incinerator it is only possible to incinerate wet sludge cake. From a technical point of view some further investigations are required to evaluate the behaviour of manure cake in the incinerator as compared to that of sewage sludge. Potential risks could be related to a different composition of the manure cake (for instance more K) possibly leading to a stronger fouling and slacking of the furnace and/or steam boiler.

The amount of electrical energy that can be produced with the current incineration process is limited. In future, a new steam generator (40 bar steam pressure) will be of interest in order to improve the electric energy production. In that case also manure cake with less water and probably also dry cake can be incinerated in combination with a much higher production of energy.

Compared to phosphate rock, the ashes from pig manure incineration contain in general: less P_2O_5 but more Cu, Zn, Fe K, Na and SO_4 .

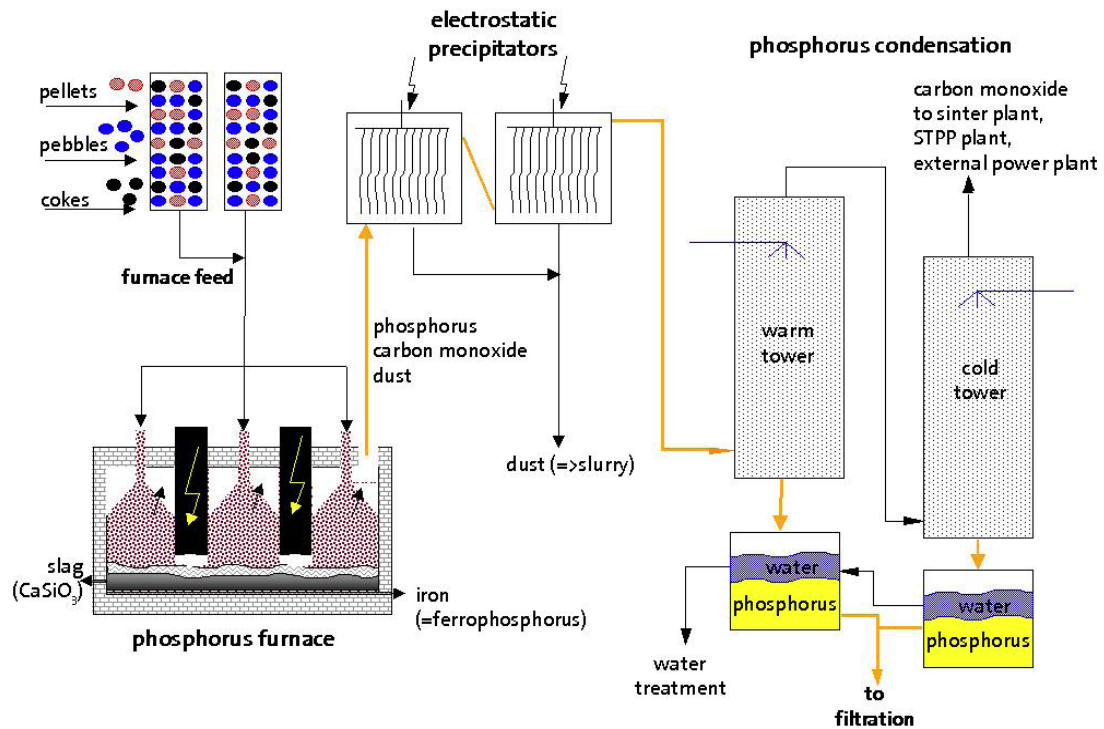


Figure 3

Phosphorus furnace section process (Source: Schipper et al., 2007).

SNB is willing to explore the possibilities of manure incineration. Compared to ashes from sewage sludge, ashes from manure will have less Fe and, therefore, can be used by Thermphos as a substitute for P-rock. However, the feasibility of using ashes from incinerated manure cakes has to be tested in practice first. The use of ashes from sewage sludge in the Thermphos process has been proven in full scale pilots at SNB and Thermphos and will soon be regular operation.

3.2 Phosphorus fertilizer production

3.2.1 Drying of wet solid manure cake

If direct application of the wet solid manure cake in agriculture is not possible further treatment of the wet solid manure fraction is necessary. In general a drying process has to be applied as a first treatment step. Drying is necessary if:

- The wet manure cake is used in an incineration process with energy recovery to produce P_2O_5 containing ash and electrical energy.
- The wet manure cake is used for a pyrolysis process to produce P-biochar.
- The wet manure cake is used for the production of dry manure pellets that can be exported as a fertilizer.

The drying process of the manure requires thermal energy. In case of incineration of manure cake in combination with the production of electrical energy the required heat for the drying process of the wet solid manure cake is produced as waste heat. A further advantage of the combination of drying and incineration is that the waste gasses of the drying process can be used as incineration air in the combustion process. This means that for the treatment of the off gasses a very advanced system to achieve low concentrations of ammonia and odour in the exhaust gases is not directly required. For the production of P-biochar very probably also an external source of waste heat is necessary. This depends on the conversion percentage of the organic matter. If part of the energy is obtained from the incineration of pyrolysis gas and/or pyrolytic oil also here the off gasses from a dryer can be used as incineration air in the pyrolysis process.

To produce an organic fertilizer for export an external source of waste heat is necessary for the drying process. The complexity of the treatment of the off gasses depends on the incineration facility at the location where the waste heat is produced. After the drying process a pelletizing step is necessary. This step requires also energy. An important aspect is that the temperature regime of the drying material is adequate to remove pathogens and weeds. This can make the drying process more complicated compared to the drying process that is used in the incineration and pyrolysis process. An interesting alternative might be the combination of drying and incineration with production of electrical energy. In general more waste heat is available than necessary for the drying of the amount of wet cake that is incinerated. The surplus of waste heat can be used for the production of dried manure granules as fertilizer for export. This combination can lead to a very flexible system for the treatment of wet manure cake.

3.2.2 Treatment of ash of incinerated manure cake

ICL Fertilizers Europe produces some 500,000 tons fertilizers in the Netherlands (equivalent to 95 million kg P_2O_5 per year) and 300,000 tons fertilizers in Germany (equivalent to 40 million kg P_2O_5). Following consultations with ICL Fertilizers Europe and some preliminary calculations, we estimate that ICL Fertilizers Europe can utilize in the short term 60,000 tons of ashes per year (6 million kg P_2O_5) derived from incinerated manure cakes. The necessary technique has been developed during the past years.

ICL Fertilizers Europe has less limitations than Thermphos in using ashes:

- The presence of NH_3/NH_4 in the ashes is not a problem;
- The presence of small amounts of carbon is not a problem;
- The P content must be at least 10% P_2O_5 (weight), which can be easily reached based on treatment of pig slurry;
- There are no strict limitations as regards the Fe content.

However, there are limitations in relation to the heavy metal content (e.g. Cd, Cu and Zn) due to agronomic constraints. Furthermore, the availability of P in fertilizers derived from ashes is still uncertain.

The production of fertilizer from ashes via a thermo-chemical method involves the treatment of the ash at 1000 °C to remove the heavy metals from the ash and to increase the bio-availability of the phosphates in the ash. This process is being developed with partners in Austria and Germany and has been proven on pilot scale. A first installation with a capacity of 20,000 ton ash per year is now being planned in Berlin. The process produces a magnesium enriched di-calcium phosphate that can be marketed as a fertilizer. The product is

already recognized as a fertilizer in Germany and Austria and recognition is expected to be possible in the Netherlands as well.

An alternative is wet chemical extraction that is being developed in cooperation with companies that have experience to treat low quality phosphate rocks. This process would allow producing animal feed quality phosphates. This process still needs further testing, but laboratory experiments have shown promising results until now.

3.2.3 Biochar production

Biochar is one of the products of the pyrolysis of organic matter. In a pyrolysis reactor, the organic matter (biomass, residues, manures, wastes, etc.) is heated under pressure in an oxygen-free atmosphere to a temperature between 350-700 °C. The pyrolysis process releases three main products:

1. A gaseous fraction containing a large variety of components such as methane, carbon monoxide, carbon dioxides, hydrogen, etc.;
2. A liquid fraction consisting of tar and pyrolytic oil;
3. A (bio)char consisting of carbon and inorganic material, including P-rich ashes.

The relative amounts of these products not only depends on the initial composition of the organic resource that is pyrolyzed but also on the process conditions such as maximum heating temperature, duration and the rate of heating. A fast heating process produces more pyrolytic oil and a slow heating process results in a higher level of carbonisation and hence more biochar.

There is an increasing research interest worldwide in the pyrolysis of biomass and organic residues, mainly for the following reasons (Lehman, 2007, 2009; Lehman and Joseph, 2009; Sohi et al., 2009; Steinbeis et al., 2009; Spokas and Reicosky, 2009; Cayuela et al., 2010):

- pyrolysis can be a way to utilize the energy from biomass and organic wastes;
- it produces a biochar that may have soil quality amending properties (i.e., improving soil structure, water holding capacity, nutrient resources and retention, etc.);
- pyrolysis of organic resources and the application of the resulting biochar to soil may contribute to mitigation of greenhouse gas emissions, notably CO₂ and N₂O, also through the sequestration of C in soil.

Chars are also produced through the gasification of organic matter. Gasification is a process in which organic matter is partly combusted and heated in an atmosphere with an oxygen amount substantially lower than the stoichiometric amount for complete combustion. The products of gasification are heat, a low caloric gas containing carbon dioxide, hydrogen, carbon monoxide, methane and other hydrocarbon components and a char (also called fly ash) containing inerts originally present in the waste (e.g. Pels et al., 2004). The amount and quality of the char are much less when produced through gasification than through pyrolysis.

We explored the potentials of pyrolysis of solid manure fractions (see also Annex 1). A total of 6 solid manures (pig, poultry and cattle) were pyrolyzed at 300-700 °C and the resulting biochars tested for its soil quality amending properties. The results can be summarized as follows:

- Production of biochar from solid manure is very well possible. The weight ratio of solid manure (dry) to biochar (in the studied materials) is about 3, indicating that two-thirds of the initial weight of the solid manure has been lost in the form of pyrolysis oil, gases and water vapour.
- Following incubation of the biochars with soils, the P availability of the soils increased significantly, suggesting that the phosphorus from the biochar released plant-available phosphorus to soil.

- Phytotoxicity tests using wheat, radish and lettuce as test plants, indicate that some biochars produced from manure at 300-400 °C retard the root and shoot growth relative to the control and biochars produced from wood biomass at 500-600 °C.
- Anaerobic mineralization tests indicate that significant amounts of nitrogen are released during incubation of the biochars produced at 300-400 °C, much more than expected.
- Further incubation tests of biochars with soils indicate that the biochars produced at 300-400 °C increase the emissions of the greenhouse gas nitrous oxide (N₂O), contrary to what was expected on the basis of results presented in literature.

In summary, this is the first time that biochars have been produced from pig, poultry and cattle manure, and tested for its soil amelioration potentials. Following application to soil, the biochars mineralized C, N and P more than expected. Further testing is needed of biochars produced at temperatures of 400-600 °C, as well as an overall assessment of the pyrolysis of solid manures and of the soil amelioration potentials of the resulting biochars.

3.2.4 Calcium phosphate and struvite production

Although the P content of the liquid manure fraction (derived from the separation of pig slurry) is considerable lower than the P content of the solid manure fraction (Schröder et al., 2009), there is still a substantial amount of P in the liquid manure fraction. Depending on the characteristics of the pig slurry and the separation technique, about 5-30% of the pig slurry phosphate is present in the liquid phase and 70-95% in the solid wet manure. The P in the liquid fraction can be recovered as a P-rich solid through precipitation processes.

Basically, adding concentrated hydroxides to the liquid manure fraction results in the precipitation of phosphates. Addition of calcium hydroxides results in the precipitation of calcium phosphates, while adding magnesium hydroxides in combination with potassium chloride will produce struvite. However, pre-treatment of the liquid fraction is needed for an effective and efficient production of calcium phosphates or struvite from the liquid manure fraction. Both precipitation pathways are used in practice; for example in the treatment of liquid manure from calves, as well as in some sewage treatment plants.

The precipitation of calcium phosphates or struvite from the liquid manure fraction is most effective when P is present as inorganic compounds. In most cases, a significant P fraction is organically bound and present as phytates and lipids, and these may not end up directly as precipitates. In such cases, an initial hydrolysis step will be needed in which organic compounds such as esters, amides, (phosphor)lipids will break down into smaller compounds like inorganic and organic acids, amines, lipid acids, amino-acids, etc. It is as yet unclear how much phytate will be decomposed due to this hydrolysis process. Probably the presence of the enzyme phytase will stimulate the decomposition of phytates.

In agreement with the Ministry of Economic Affairs, Agriculture and Innovations the focus of the following study will be more on the purification of the liquid manure fraction.

3.3 Some additional remarks

The previous sections explored the possibilities for large-scale recovery of P-rich products from pig slurry, using existing processing technology and existing marketing and sales infrastructure for exporting the resulting P-rich products to countries with a need of these products. The purpose of exploring these possibilities was threefold:

1. to drastically lower the P surplus in agriculture in the Netherlands in a cost-effective way and at relatively short term, and

2. to recover the excess P in a form that can be transported to and utilized in other countries rather easily.

In the long term, additional opportunities may appear for utilizing the excess P in agriculture in the Netherlands, such as

- the treatment of (diluted) liquid manure phases by algae in large-scale plants to produce biomass for a bio-based economy;
- the selective removal of phosphate containing particles (suspended solids) from manure, using newly developed techniques;
- the clustering of crop and animal production in agro-production parks aimed at increasing resource use efficiency (e.g. Smeets, 2009).

It is beyond the objectives of our study to discuss these options further.

4 Overall manure treatment scheme and evaluation of options

In the previous Chapter the production of different types of P-rich manure products was described. These products can be processed further by industries that produce and market P fertilizers and other P-rich products. These P-rich manure products are derived from the solid fraction of separated pig slurry only. Disposal pathways for the liquid fraction have not been discussed yet. The preferred disposal pathway is direct application to agricultural land as NK fertilizer. However, this is not always feasible and then a further treatment will be needed.

4.1 Coherent overview

Figure 4 gives a coherent overview of all main manure processing steps, including those for the liquid fraction. Table 2 gives an overview of the defined composition of P rich manure fractions for further processing by treatment plants or industries, based on the discussion with the industries.

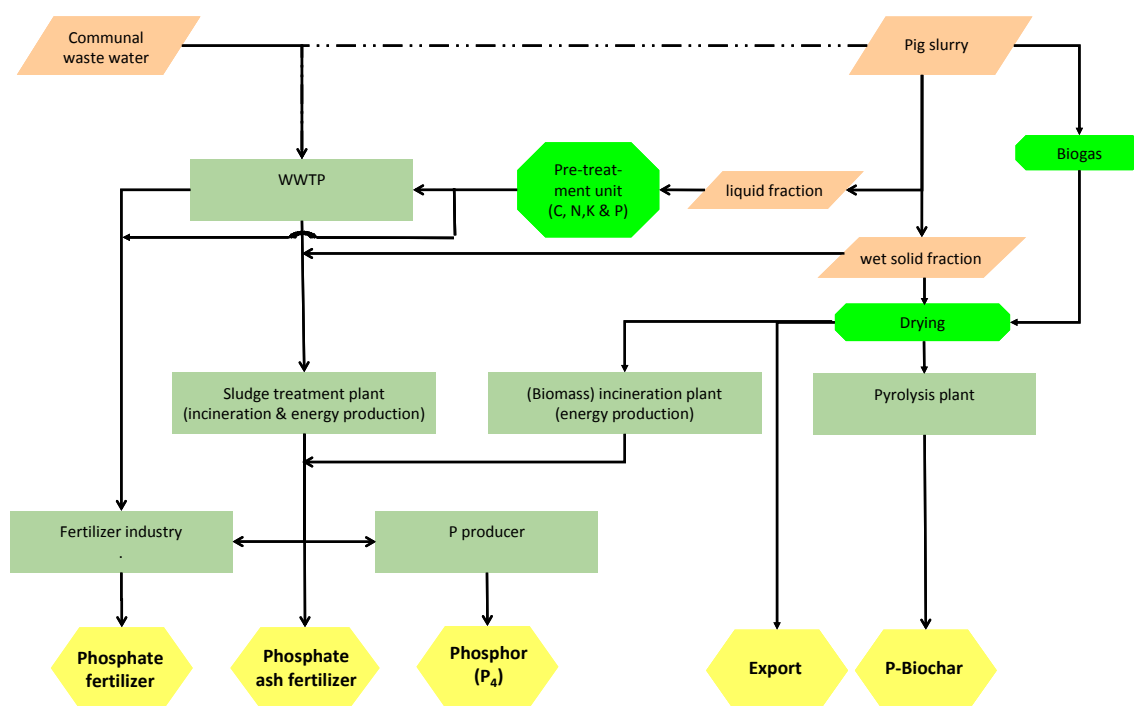


Figure 4

Overview of marketable P products from manure to existing markets and processing techniques needed.

Table 2

Defined composition of P rich manure fractions for further processing by treatment plants or industries (mass per cubic metre material; kg m⁻³).

	Pig slurry ¹⁾	WWTP (not treated)	WWTP (treatment N-strip & particles)	Sludge Treatment Plant	Incineration Plant	Pyrolysis Plant	Fertilizer industry precipitate	Fertilizer industry ash	P ₄ industry
Water	927	>965	>965	750-800	<400	<400	<500	<20	
Dry solids	73	15-35	15-35	250-200	>600	>600	>500	>980	
- Inorganic (ash)	22	9-15	9-15						
- Organic	51	6-20	6	140-175	>500	>500	<50		
Chemical Oxygen demand (COD)		6-20	6						
N-Kjeldahl	6.3	4.8	0.9						
- Ammonium (NH ₄)	4.3	4.3	0.4						
- Organic N	2	0.5	0.5						
P(as P ₂ O ₅)	3.7	0.2-0.4	<0.3				>100	>100	>200
Fe									<2
Zn	0.07								
Cu	0.03								
pH	7-8	7-8	8.5						

¹⁾ Römken and Rietra (2008).

In Appendix 1 the different routes indicated in figure 4 for P recovery from manure as fertilizer, pure P (P₄) or dried cake containing P are described including techniques for elimination / recovery of other components present in the manure and recovery of energy from the organic components present in the manure. Furthermore, the advantages and disadvantages are mentioned and some rough information on costs is given. The separate steps for P recovery from manure are:

Complete treatment

- Traject 1: complete treatment of the manure at WWTP

Pre-treatment

- Traject 2: mechanical separation of the manure at farm scale and treatment of liquid fraction regional and treatment of the wet solid fraction elsewhere (regional/central)
- Traject 3: mechanical separation of the manure and treatment of liquid fraction regional and treatment of the wet solid fraction elsewhere (central; e.g. SNB, Themphos)
- Traject 4: digestion, separation, drying at farm scale, treatment liquid fraction regional and treatment of the wet solid fraction elsewhere (regional/central)

Processing P resources for the industries

- Traject 5: production of P biochar from partly dried or dry solid cake
- Traject 6: production of P₄ from wet or dry solid cake
- Traject 7; production of fertilizer components from the solid manure fraction
- Traject 8: production of fertilizer components from the liquid manure fraction

Several scenarios can be devolved based on different combinations of the Pre-treatment and processing steps.

4.2 Complete treatment of manure at a WWTP

A complete treatment of pig slurry at a WWTP (Route 1) is not a logical/feasible pathway, because of the relatively large contents of organic matter and nutrients in the pig slurries, which are not recovered in WWTP's, and because of the fact that WWTP's are primarily focused on the treatment of municipal wastewater. Furthermore, the liquid fractions derived from especially cattle slurry may be applied to the land of the farm where the slurries are produced, considering also the relatively high N/P ratio. When treated at WWTP's, the liquid fraction should be purified from elements such as residual amounts of organic carbons, humic substances, nitrogen and phosphorous, metals, etc., before it can be discharged to surface waters (via WWTP). This treatment will be discussed later.

4.3 Mechanical separation and anaerobic digestion

A first step in manure treatment is the mechanical separation of slurries into a liquid fraction and a solid fraction. This separation can be done at the farm itself (Route 2) or at a central location in a region (Route 3). Different techniques are available and these have been evaluated by Schröder et al. (2009). At farm scale, the low tech separation techniques seem to be the most cost-efficient. A possible option would be to build large units for mechanical separation close to WWTP's for a possible joint processing of slurries and certain wastes and also to reduce transport costs of a possible treatment of the liquid fraction at the WWTP. The regional treatment process of manure has not to be limited to a mechanical separation only, but may also include a digester, a membrane separation unit, a stripper for ammonia, a dryer, etc.

Anaerobic digestion of pig slurries produces a relative small amount of biogas per cubic meter. Co-digestion will result in a higher biogas production. The biogas can be used for electricity production by means of cogeneration and the waste heat of the cogeneration can be used for the drying of the wet solid fraction into a dry manure cake. Co-digestion will result in an increase of the manure amount. It is also possible to increase the amount of biogas by a pre-treatment step of the manure (Timmerman and Rulkens, 2010a). The biogas production of cattle and pig slurry is around 20 to 30 m³ biogas per ton. Through pre-treatment, the biogas production may rise by 50% or with 10 to 15 m³ biogas per ton of manure. In a CHP-installation this would lead to extra revenue of € 3.20 to € 4.80 per ton of pig manure slurry. The costs of pre-treatment need to be low in order to be economical feasible. As a consequence, pre-treatment of slurries to increase the biogas production on a farm are not economical feasible at this moment. There is also no practical experiences with pre-treatment technologies for manure slurry at farms (but there are experiences from research).

4.4 Drying of solid fractions

Drying of the solid fraction of manure decreases the transport costs and increases the opportunities for processing via incineration and pyrolysis and for export to abroad. Information on the transport costs and drying costs are presented in Table 3. Drying of manure cake can be executed at farm scale (Route 4) but also at the manure treatment unit in the region. Timmerman and Rulkens (2010b) studied different methods to dry the manure: convection dryers, conduction dryers and radiation dryers. Conduction dryers offer the best perspective for use at a biogas plant. However, there is no need for drying of the solid manure cake if the current incineration process of SNB is used for manure incineration, because the incineration process of SNB is only suitable for wet sludge and wet manure. A proper mechanical separation process should be used to create the right water content of the cake.

Table 3

Calculation of transport costs in 2010 (based on transport of 36 ton manure material).

		Pig slurry ¹⁾	liquid fraction	solid fraction (wet cake)	solid fraction (wet cake)	solid fraction (wet cake)	dried solid fraction	dried solid fraction
			(3%-5% DM)	(20% DM)	(25% DM)	(30% DM)	(60% DM)	(90% DM)
activity	unit							
filling & unloading truck	hours	1	1	1	1	1	1	1
transport distance vice versa	km	100	100	200	200	200	200	200
travel time	hours	2	2	4	4	4	4	4
total time transport	hours	3	3	5	5	5	5	5
cost truck ¹⁾	€/hours	65.00	65.00	65.00	65.00	65.00	65.00	65.00
Total transport cost	€	195	195	325	325	325	325	325
Adm. costs Manure Act ¹⁾	€	55	55	55	55	55	55	55
Total costs per 36 ton	€	€ 250.00	€ 250.00	€ 380.00	€ 380.00	€ 380.00	€ 380.00	€ 380.00
costs per ton material	€/ton	€ 6.94	€ 6.94	€ 10.56	€ 10.56	€ 10.56	€ 10.56	€ 10.56
fraction of original slurry	-	1	0.74	0.33	0.26	0.22	0.12	0.08
costs per ton original slurry	€/ton	€ 6.94	€ 5.14	€ 3.48	€ 2.74	€ 2.32	€ 1.27	€ 0.84

¹⁾ Pers comm. CUMELA.

4.5 Costs of pig slurry separation, drying of solid fractions and transport

The economic costs of pig slurry separation, drying of solid fractions, and the costs of transport of liquid and solid fractions at farm scale and region scales are shown in Table 4. The likely composition of the liquid and solid fractions is shown in Table 5. The following assumptions were made:

- the ratio between inorganic and organic components of the dry solids is 1:3:5 and the ratio of ammonia and organic nitrogen 3:1 after separation;
- if the manure is dried the ammonia concentrations in the dried material will be less than 1 kg m⁻³ in the material;
- the amount of P in solution is small (max. 0.34 kg P₂O₅ per ton) compared to the amounts of P₂O₅ in the slurry (3.7 kg per ton),
- the costs of drying are at least in balance with the profits of electricity production if the dried manure cake is incinerated in an installation with energy recovery;
- the mechanical separation technique will be more cost-efficient when applied at regional location (25% lower costs, corresponding with 3 Euro) than at farm level (4 Euro per m³);
- the manure is transported to a treatment point in the region where the liquid fraction can be further treated or partially treated followed by transport of the partially treated effluent to a WWTP in the vicinity of the regional manure treatment plant for final treatment.

Manure separation can be highly cost-efficient on dairy farms, especially on farms that have to export slurry (because of too much P), and import N fertilizer (for increasing forage production). In these cases, the liquid manure can be applied at the farm where the manure was produced as NK fertilizer. Only the wet solid fraction needs to be transported.

The costs of drying manure cake highly depend on the target dry matter content (Table 4). There is not much difference in total costs between mechanical separations plus drying of the solid fraction at regional scale compared farm scale. Dried manure cake can be exported directly (as soil amendment) or following incineration into P-rich ashes or pyrolysis into biochar. Further, the ashes and biochar can be treated further to generate elemental P.

Table 4

Costs of pig slurry separation, drying of solid fractions, and the costs of transport of liquid and solid fractions at farm scale or in the region.

	Separation at the farm			Separation at the region		
	pig slurry	pig slurry	pig slurry	pig slurry	pig slurry	pig slurry
Input						
Transport	no	no	no	transport of manure	transport of manure	transport of manure
Treatment	separation no drying	separation drying; co-digestion/ cogeneration low energy	separation intensive drying; co-digestion/ cogeneration energy	separation no drying	separation drying; co-digestion/ cogeneration low energy	separation intensive drying; co-digestion/ cogeneration energy
Transport	transport of liquid fraction to pre-treatment unit WWTP	transport of liquid fraction to pre-treatment unit WWTP	transport of liquid fraction to pre-treatment unit WWTP	no (liquid)	no (liquid)	no (liquid)
	transport of wet solid fraction (to sludge treatment plant)	transport of dried solid fraction (to incineration or pyrolysis plant)	transport of highly dried solid fraction (to incineration or pyrolysis plant)	transport of wet solid fraction (to sludge treatment plant)	transport of dried solid fraction (to incineration or pyrolysis plant)	transport of highly dried solid fraction (to incineration or pyrolysis plant)
Costs (€ m ⁻³ fattening pig slurry)	no drying	limited drying (60% DM)	drying (90% DM)	no drying	limited drying (60% DM)	drying (90% DM)
Transport manure				6	6	6
Mechanical separation	3-5	3-5	3-5	2-4	2-4	2-4
Drying		5-6	7-8		5-6	7-8
Transport liquid fraction	5	5	5			
Transport solid fraction	2	1	1	2	1	1
Total	10-12	14-17	16-19	10-12	14-17	16-19

Table 5*Indicative composition of fattening pig slurry and treated pig slurry (kg m⁻³).*

	Ratio	Pig slurry ¹⁾	Liquid fraction	Solid fraction (wet cake)	Solid fraction (wet cake)	Solid fraction (wet cake)	Dried solid fraction	Dried solid fraction
			(3%-5% DM)	(20% DM)	(25% DM)	(30% DM)	(60% DM)	(90% DM)
Water		927	950-970	750-850	700-800	650-750	350-450	100
Dry solids		73	30-50	150-250	200-300	250-350	550-650	900
- Inorganic (ash)	1	22	7-11	30-50	45-70	50-75	150-200	200-300
- Organic	3.5	51	23-39	120-200	155-230	200-275	400-450	600-700
Nkjeldahl		8	1-4	22	27	33	16	24
- Ammonia	3	6	0.7-3	16	21	25	<1	<1
- Organic	1	2	0.3-1	5	7	8	16	24
P as P ₂ O ₅		3.7	0.5-2	10	13	15	30	46
K as K ₂ O		8.0	8.3	6.9	6.5	6.0	12	18

¹⁾ Römken and Rietra (2008).

4.6 Incineration of manure cakes: production of ashes

Dried solid (pig) manure cake or wet solid (pig) manure cake can be incinerated to produce P-rich ashes. At the short term wet solid pig cake can be incinerated at sludge or biomass incineration plants, like those of SNB. Dried solid pig cakes can technically incinerated at e.g. BMC or Fibroned. In all cases the capacities are not sufficient to deal with the whole manure surplus.

Pilot studies have to be carried out to test the incineration route. For example, 10-25% of the capacity of SNB can currently be used for manure incineration, which equals to about 65,000 ton manure cake (25-30% dry matter) and 1 million kg phosphate. The processing costs will be approximate 10-15 Euro per ton wet manure cake. To incinerate dried manure cake with energy production, a dedicated new incineration plant (steam pressure 40-65 bar) has to be built (new factory/plant). In that case the capacity and the energy production can be increased remarkably and the net treatment costs will be less. Such an installation would then only or mainly incinerate dried manure (60%-90% dry matter) and this could result in an ash of a better quality than when the manure is co-incinerated with sewage sludge. Based on the investments cost of the biomass plant in Moerdijk (146 million Euro and a capacity of 440,000 ton dried manure) it is expected that the incineration of manure will be more or less cost neutral when the energy production from manure is taken into account (see hereafter for detailed cost estimation; Table 6).

For the processing of P-rich ashes into P fertilizer products, the fertilizer industry will need a flexible proportioned unit and some silo's for temporary storage of the products. These investments seems to be rather low, about 1-2 million Euro (personal comm. ICL). If a total amount of 20 million kg phosphate in ash from pig slurry is being processed annually, the investments costs will be much less than 1 Euro per m³ pig slurry. In the view of ICL-Fertilizers the ashes derived from pig slurry should be delivered for free. They expect that the costs for producing and marketing P fertilizers from ashes are higher than in the case of using P rock resources. A flexible proportioned system has to be built to allow the processing of variable amounts of ashes in time. Probably, no covenant is needed for guaranteed delivery. Furthermore, they want only the manure resources as ash, because they make only inorganic fertilizers.

4.7 Pyrolysis of manure cakes: production of biochars

To date, the production of biochar is still a speciality. Biochar is a product of the pyrolysis of biomass or organic waste. The market prices of biochar are relatively high compared to fertilizers (about 5 times higher in relation to the P content). The increasing interests to produce biochar are caused by the claim that biochar may improve the soil quality and may contribute to fewer emissions of greenhouse gasses. To date there is not much experience with the production of biochar from animal manure and the long-term added value of a nutrient rich P-biochar is not yet known. Nevertheless, if a part of the P surplus can be exported as biochar product, it can become a worthwhile and profitable product from at least an economical point of view. The production process of P-biochar, the agricultural quality regarding the nutrient availability (P release and N mineralization), the possible phytotoxicity effects and the emission potentials are the main points of research in our study. At first different types of manure: poultry, pig and cattle samples were pyrolyzed at temperatures in the range of 300-400 °C and the results are described by Ehlert et al. (in prep.). It was concluded that pyrolysis of dried manures should be done at temperatures of 400 to 600 °C. Pyrolysis at lower temperature (300 °C) less syngas and oils were formed, the C:N and C:P ratio were still relative high and the availability of N (mineralisation rate) and P (extractable P) were less than in the original manure, but higher than expected. A rough indication of the production costs of P-rich biochar from dried manure cake (60% DM) is 4 Euro per ton pig slurry, if no price is paid for the P resources of the manure. These costs will be reduced to approx. zero if 5 times the prices of rock phosphate will be paid (see hereafter for detailed cost estimation; Table 6).

4.8 Further processing of ashes into elemental phosphorus and fertilizers

In theory, very large amount of manure cakes can be disposed of via Thermphos, Western Europe's biggest P producer or via ICL fertilizers, following the incineration of the manure cakes into ashes and the further processing of the ashes to elemental P or fertilizer P. Currently, Thermphos uses already ashes from WWTP following incineration of sewage sludge at SNB, namely the sludge with low Fe-content (see Chapter 3). The elemental P produced from the ashes is used for the production of all kind of products, almost exclusively outside agriculture. However, Thermphos has no direct experience with the processing of ashes from manure cakes and the presence of several impurities (copper, zinc) is expected to decrease the value of the ash as raw material as these lead to processing problems or less efficient processes. Thermphos is willing to explore the perspectives of the manure ash if the composition of the manure ash is in line with their conditions. It seems that this will be possible. Furthermore, a full size practical experiment is necessary to set up the production of elemental P out of manure ash and to evaluate the advantages and disadvantages.

A large-scale experiment at Thermphos requires the equivalence of about 5-10 million kg P as manure ash. Without such an experiment there will be no implementation of this route. At present, also Thermphos want to have the manure ash for free. The costs related to the processing and marketing of the elemental P produced from manure ash will be covered by the sales of the elemental P and will be dealt with by Thermphos. However, the first step is the experimental set up of a large test at Thermphos (delivery of manure by farmers, mechanical separation, a solution for the processing of the liquid part, incineration of the wet manure cake at, for example, SNB and collection of the ash at Thermphos and testing). Following a successful experiment, a covenant is needed between the agricultural sector and Thermphos with respect to the guaranteed delivery of manure (ash) for at least 10 years. Furthermore, attention has to be paid regarding production and transport permissions (legislation).

4.9 Treatment of the liquid fraction

The liquid fraction resulting from the mechanical separation of pig slurry cannot be handled via Thermphos and ICL fertilizers. This fraction has low nutrient and organic matter contents, and is preferably disposed of nearby on agricultural land. If the latter is not possible, it has to be treated, because transportation is associated with high cost due to the high water content.

There are two main routes for the treatment of the liquid fraction: (i) separation of solids and salts from the water via ultra-filtration and reverse osmosis, and (ii) the removal of residual carbon, nitrogen, phosphorus and metals through precipitation, stripping and oxidation. The first route yields 'mineral concentrates' to be used as NK fertilizers and water to be discharged to surface waters. This route is extensively researched within the pilot project 'Mineral concentrates' (Velthof et al., 2010). The second possible route is further discussed below.

The residual P in the liquid fraction can be recovered following precipitation of calcium phosphates or struvite. The NH_3/NH_4 can be recovered partly following precipitation of struvite or by stripping and subsequent absorption of the stripped NH_3 into sulphuric acid (see Chapter 2). The precipitates of phosphate may be added to the wet manure cake. The obtained ammonium sulphate may be used by the fertilizer industry to produce N fertilizer. The residual liquid fraction will have to be treated at a WWTP before it can be discharged to surface water, because of the relatively high residual ammonia and organic components.

The amount of municipal wastewater is about 1500 million m^3 in the Netherlands. The amount of water in the equivalent of 20 million kg phosphate as manure is about 5 million m^3 , and relatively small compared to the total amount of water processed at the WWTP's. All WWTP are more or less independent business units, with own procedures and treatment schemes. To be able to explore the possibilities of the treatment of the residual liquid fraction at WWTP's, we consulted the branch organisation STOWA. Their advice is to purify the liquid fraction in a separate treatment plant nearby a WWTP. We estimated that the cost for P precipitation and NH_3/NH_4 precipitation or stripping is about zero, if the acids are delivered by the fertilizer industry and the precipitates and ammonium sulphate solution are delivered back to the fertilizer industry.

4.10 Cost calculations for large-scale manure processing

Table 6 gives an overview of the estimated costs of producing P-rich ashes and biochar from manure cakes. The cost calculations assume that the equivalence of 40 million kg of P_2O_5 as pig slurry has to be processed. In the first block of Table 6 the input material is defined, in terms of dry matter content of the manure cakes and biochar. In all cases, the equivalence of 600,000 ton dry manure cake has to be processed. Note that the net energy recovery is low for wet manure cake.

The estimated investment costs of the new incineration plant are derived from recent experience of the building of the biomass plant in Moerdijk. The actual costs were about 105 million Euro. Another 40 million was necessary for the project as a whole (consultations, permits and licences, etc.). We used a value of 150 million Euro for the same capacity available in Moerdijk (440,000 ton materials). An annual depreciation and interest costs of 10% and operational costs of 5% is reasonable for such constructions. The total operational costs for the incineration of dried material range between 34 and 51 million Euro per year. The total operational costs for the incineration of wet manure cake are 136 million Euro.

The gains are related to energy production and P recovery. The incineration value of dry manure ranges between 14,000 and 17,000 MJ per ton dry matter (REF). In this study we used an average value of 15,500 MJ, and an energy price of 9 Eurocent per kWh. In the case of pyrolysis, we assume that there is no net energy recovery. Further, we assume that the phosphorus industries will pay a similar price for the P in ashes as they do now for that in rock phosphate (0.25 Euro per kg P₂O₅). For the P in biochar, we assume that the price is 5 times higher because of the expected beneficial value when used as soil amendment.

Table 6

Costs of treatment of the solid fraction of fattening pig slurry.

To be produced:	P ash	P ash	P ash	P biochar
Input material for plant:	wet manure cake	limited dried manure cake	dried manure cake	dried manure cake
Dry matter content (%)	22.5%	60%	90%	60%
- Inorganic (ash) (kg/ton)	5	13	20	13
- Organic (kg/ton)	18	47	70	47
P ₂ O ₅ (kg per ton material)	15	40	61	40
Amount input material (million ton)	2.67	1.00	0.66	1.00
Amount dry matter (million ton)	0.60	0.60	0.60	0.60
Fraction of original material (PS) (%)	23%	9%	6%	9%
Type of treatment plant	existing incineration plant	new incineration plant	new incineration plant	new pyrolysis plant
Electric energy rendement plant (%)	5%	20%	25%	20%
Investment plant (million €)	910	340	225	340
Annual depreciation + interest (10%) (million € y ⁻¹)	91	34	22.5	34
Operational costs (5%) (million € y ⁻¹)	45.5	17	11.25	17
Total annual costs (million € y⁻¹)	136.5	51	33.75	51
Net energy benefits (million € y ⁻¹)	11.6	46.5	51.2	0
Phosphate benefits (million € y ⁻¹)	10.0	10.0	10.0	50.0
Total annual benefits (million € y⁻¹)	21.6	56.5	61.2	50.0
Net annual costs (million € y⁻¹)	114.9	-5.5	-27.4	1.0
amount of P processed solid (10 ⁶ kg)	14.0	14.0	14.0	14.0
Net cost per kg P produced	8.2	-0.4	-2.0	0.1
amount of pig slurry (million ton)	11.8	11.8	11.8	11.8
Net cost per ton pig slurry	9.8	-0.5	-2.3	0.1

The lower half of Table 6 shows the net costs of incineration and pyrolysis of manure cakes, expressed in terms of Euro per kg P and per ton pig slurry. Evidently, incineration of wet manure cake is not efficient. If the manure is dried first (DM 60%) or intensively dried (DM 90%) the benefits are higher than the costs and the net benefits vary between 0.5 and 2.3 Euro per m³ pig slurry. The pyrolysis plant is 'in balance / break even point', due the assumed high value of the biochar.

In Table 7, the overall net costs for the production of ashes from pig slurry are presented taking into account all the processing steps: separation, drying and the treatment of the liquid fraction at a WWTP. If dried manure is used the overall costs range between 24 and 31 Euro per m³ pig slurry.

Table 7

Indicative costs to produce P ash from manure as a P resource for industries (€ m³ pig slurry).

	No drying	Limited drying (60% DM)	Limited drying (90% DM)
Separation, optional drying and transport solid fraction	5-7	9-12	11-14
Transport liquid	5	5	5
Treatment solid fraction	9.8	-0.5	-2.3
Treatment liquid fraction	11-14	11-14	11-14
Total	31-36	24-30	25-31

4.11 Some concluding remarks

There are various options for the recovery of P from manure. However, it is impossible to make 'brown gold' from manure. The value of manure is determined by the contents of organic matter and nutrients, and by the perceived 'added value' of manure when applied to crop land. The latter value depends on the user. The value of organic matter and nutrients ranges together between 6-11 Euro per m³ pig slurry (Table 8).

Table 8

Intrinsic value of pig slurry.

	Content ¹⁾ (kg/m ³)	Market price ²⁾ (€/kg)	Market price ²⁾ (€/kg)	Total (€/m ³)	Total (€/m ³)
Nitrogen anorganisch (N)	3	0.204	0.476	€ 0.61	€ 1.43
Potassium (K ₂ O)	8	0.128	0.298	€ 1.02	€ 2.38
Phosphate (P ₂ O ₅)	3.7	0.234	0.546	€ 0.87	€ 2.02
Organic matter (solid phase)	40	0.091	0.117	€ 3.64	€ 4.68
Total (€ m³)				€ 6.14	€ 10.51

¹⁾ Römken and Rietra (2008); content of inorganic N, P₂O₅ and organic matter; content of K₂O estimation.

²⁾ LEI land- en tuinbouwcijfers 2008; 15-35% of the fertilizer market prices: KAS (N), TSP (P₂O₅) en K60 (K₂O) and value of energy production of organic matter (based on 7-9 Eurocent per kWh).

The value of organic matter, on the basis of its energy content, is highest (Table 8). However, energy is needed to recover the energy and nutrients from manure and that will reduce the value of manure for the farmers. The value of the energy and nutrients are related to the oil price; the higher the oil price, the higher the value of the organic matter and nutrients. Further, the value of phosphorus will likely increase in the near future, due to the increasing scarcity of P rock reserves. As a result, the intrinsic values of manure will increase in the near future.

5 Discussion, conclusions and recommendations

5.1 Increasing need for manure processing

The step-wise lowering of the phosphorus (P) application standards for agricultural land during the last decades has decreased the room for manure application. As a consequence, an increasing amount of manure cannot be applied on the farms where the manure is produced. The surplus of manure has to be transported to other farms, including those abroad, with or without prior treatment. This transport and additional treatment have increased the cost of manure disposal and threatens the economic profitability of animal husbandry in the Netherlands.

The P application standards for agricultural land will further decrease during the next years. Forecasts suggest that the total amount of animal manure produced in the Netherlands by 2015 will exceed the total amount of animal manure that can be applied to agricultural land in the Netherlands by an equivalent of 40-60 million kg P_2O_5 per year. The actual surplus will depend on the economic development of the livestock sector, the success of animal feeding strategies to lower the amounts of nitrogen and phosphorus in the manure, and on further environmental and legal restrictions. Weather conditions may greatly contribute to inter-annual variations in surplus, because the period for manure application is relatively short and may be shortened further to decrease the risk of nitrate leaching.

Forecasting developments in the livestock sector in the Netherlands is not easy. There is general consensus that the global livestock sector will increase because of the increasing human population and the increasing consumption of animal products in some parts of the world (FAO, 2009). There seems to be also consensus that the size of the EU livestock will not change much. A number of recent studies indicate that parts of the livestock sector in the Netherlands may shrink while others may increase in size, depending on the development of world food prices, the reform of the EU Common Agricultural Policy (e.g. milk quota, farm payments), the compliance to EU environmental policies (derogation from the Nitrates Directive, ammonia emissions ceiling of the NEC Directive) and the abolishment of the pig and poultry production rights (Silvis et al., 2009; Baltussen et al., 2010; Vrolijk et al., 2010). Summarizing, the possibility cannot be excluded that the total manure production will increase in the Netherlands during forthcoming years, and thereby put additional pressure on the manure market.

There are possibilities to reduce the amount of P in manure by about 20-25% through reducing the amount of total P and increasing the amount of digestible P in feed (Van Krimpen et al., 2009). Through bio refinery, the use of imported feed resources by the feed industries can be further optimized so as to decrease the P content of the animal feed further (Meesters et al., 2010). It is expected that the manure surplus can be reduced by combining these strategies with an equivalent of 10-15 million kg P_2O_5 per year.

During the last years, an increasing amount manure has been exported to other countries, especially dried poultry manure. It is expected that the export of animal manure will remain at this high level of 20-35 million kg P_2O_5 per year during the forthcoming years (Luesink et al., 2008). A relatively large amount of dried poultry manure is incinerated at BMC in Moerdijk and this pathway also contributes to lowering the 'pressure' on the manure market. The export of untreated pig slurry to Germany has become under pressure recently, indicating that treatment will become necessary (standard) for exporting manure to other countries.

Manure processing and export are increasingly seen as a possible solution for lowering the pressure on the manure market. In the recent past, there have been various attempts to set-up large-scale manure processing, but without much success. It is believed that new and improved manure processing techniques, cooperation with relevant industries to exploit possible synergetic effects in the treatment process of manure and changes in the manure market will provide better opportunities for manure processing in the upcoming years. There is also an increasing need to economize on fossil fuel and scarce phosphorus rock resources, and these factors will also provide incentives for recovering energy and phosphorus from manure through manure processing.

We make a distinction between farm-scale manure processing techniques, to facilitate precision manuring on agricultural land in the Netherlands, and larger-scale manure processing techniques aimed at exporting the resulting treatment fractions to other countries. The farm-scale techniques will focus on manure separation, with or without prior digestion for biogas recovery, and the resulting manure fractions will be disposed off in the Netherlands. The larger-scale techniques will also involve manure separation with or without prior digestion for biogas recovery, but will include further treatment steps so as to recover phosphorus for export to other countries. Below, we focus on the larger-scale manure processing.

5.2 Large-scale processing and disposal of solid manure cakes

In order to set up a sustainable manure processing system for P recovery from especially pig slurry, products have to be produced, which can be used as a resource (feed stock) by industries or can be exported directly without much risk (related to for example the transmission of animal diseases or other unwanted incidents). In our study, we focussed on pig slurry as these slurries are produced on farms with little land, are voluminous and therefore have less alternatives (more comparative disadvantages) for disposal compared to poultry manure and cattle slurry. As indicated before, most of the poultry manure is already processed and exported (incinerated). Further, most (dairy) cattle farms are land-bound and may use simple manure separation technique to expand their total amount of manure application on agricultural land (precision manuring) or simply transport the surplus amount of P (in the solid fraction) to other farms. Note that the liquid fraction is relatively rich in nitrogen (N) and potassium (K), which may be utilized on-farm, while the solid fraction is relatively rich in phosphate (P) and organic matter (C), which are attractive for many arable farms (e.g. Schröder et al., 2009).

The industries that produce and market fertilizer P and elemental P are interested in using the P-rich solid manure fraction as feed stock. Based on discussions with various stakeholders, we distinguish four P-rich products processed from the solid manure fraction, each with a distinct market: (1) Dry organic fertilizers, (2) Mineral phosphate fertilizers, (3) Elemental phosphorus, and (4) Biochars.

5.2.1 Dry organic fertilizers

The main advantages of producing and exporting 'organic fertilizers' through drying of wet solid manure cakes are the relatively simple, robust and cheap processes, and hence relatively low costs. It can be easily organized by a group (consortium) of farmers within a region. The drying costs may be kept low through utilizing residual heat of a nearby power station or industry. Evidently, there will be a need for certification of the resulting organic fertilizer, especially as regards sanitary aspects, weed seeds and contents of heavy metals, antibiotics, etc.

The main disadvantage is that the organic fertilizers remains a relatively voluminous product, mainly for niche markets. Storage requires special precautionary measures, because of the presence of carbon and nitrogen-nitrate and also because of the risk of insufficient sanitation. As a consequence, there is some uncertainty about the long-term sustainable marketing. Furthermore, there is still need for a solution of the liquid fraction.

5.2.2 Mineral phosphate fertilizers

Mineral P fertilizers can be produced from solid manure cakes following its incineration and the subsequent processing of the resulting ashes at the phosphate fertilizer plant ICL Fertilizer Europe in Amsterdam. The incineration of the dried manure cake can be done in a stand-alone installation, at a biomass incineration plant or at BMC in Moerdijk, with energy recovery. The main advantage of this route is that a world-wide market becomes available, via the fertilizer industry, for the disposal of the surplus manure P. There seems to be no upper limit for the total amount of ashes to be processed, and there are no problems related to the storage and acceptance of the product. The processing costs of this route are not necessary higher as those for the production of organic fertilizers. Moreover, the costs for storage and transport of the ashes and resulting mineral fertilizers are much lower compared to those for organic fertilizers. Further, there are no risks associated with the transmission of animal diseases, antibiotics, hormones, etc., to other countries, because of the incineration. Also, all nutrient elements in the ashes are retained, end up in the mineral fertilizer P. However, there is as yet no experience with this route; it has to be tested in practice and evaluated in more detail. Also, the quality of the retrieved ashes and the quality of the resulting P fertilizer have to be tested (effectiveness of the P resource). Depending on the quality of the ashes, the fertilizer industry may want to pay for it.

The main disadvantages of this production route are that (1) the organic matter, nitrogen and sulphur in manure are incinerated and hence withheld from adding to soil, (2) a covenant is needed between farmers, incineration plant(s) and the fertilizer industry to ensure the delivery of large amounts of manure cakes, and (3) an additional incineration plant will be needed, like the biomass incineration plant for poultry manure in Moerdijk. Both, the covenant and the permit for setting up an additional incineration plant may take a long preparatory trajectory. Further, tests are needed at pilot scale to explore the practical feasibility. Finally, there is still need for a solution of the liquid fraction.

5.2.3 Elemental phosphorus

Elemental phosphorus production is a basic resource for many food and non-food products. It can be retrieved from the ashes of manure cakes, following its incineration, by Thermphos, the main phosphorus producer in Western Europe. The advantages and disadvantages related to the production of mineral P fertilizers from manure cakes (see Section 5.2.2.) relate also to the production of elemental P from manure cakes, and are not repeated here. In addition, the minimum volume of ashes to be processed is larger in the case of elemental P production than in the case of mineral fertilizer production, and that this volume has to be guaranteed strictly. Further, from all nutrient elements in the ashes, only P is retained, ends up as elemental P. Also, there is as yet no experience with this route; it has to be tested in practice and evaluated in more detail. The quality of the retrieved ashes have to be tested too, especially the contents of Fe, C, Cl and Cu are critical.

5.2.4 Biochars

For the production of P-rich biochars, dried manure cakes have to be pyrolyzed. Pyrolysis is a process in which organic matter is indirectly heated to a temperature of 300-550 °C in the absence of oxygen to produce pyrolytic oil and gas and char (Bridgwater, 2004; Bridle and Pritchard, 2004). The fraction of carbon, originally present in the manure cake that ends up in the char is in the order of 60-70%, depending on the temperature. The same holds for nitrogen and sulphur, while basically all other nutrient elements will end up in the char, including phosphorus. To date, the production of P-rich biochars from manure is still a speciality. The production of biochar is much more expensive than the production of ashes, because the energy yield via the pyrolytic oils and gases is low. However, the market prices of biochars are relatively high compared to ashes, because it is claimed that biochar may improve the soil quality and may contribute to lower emissions of greenhouse gasses (e.g. Cayuela et al., 2010). Our assessments indicate that the net total costs of manure processing (and disposal) via this route are similar to those via the production of mineral P fertilizers and elemental P. The advantages and disadvantages related to the production of mineral P fertilizers from manure cakes (see Section 5.2.2.) more or less also relate to the production of biochar from manure cakes, and are not repeated here. However, much more carbon, nitrogen and sulphur are retained in the biochar than in ashes from incinerated manure cakes. In addition, there is not much experience with the production of biochar from animal manure, the long-term added value of a P-rich biochar is not yet known and the markets are not yet clear. Hence, the uncertainties related to this route are relatively large, but the economic opportunities may also be large, given the increasing demands for soil ameliorating products that decrease greenhouse gas emissions.

5.3 Treatment and disposal of liquid manure fractions

The liquid fraction is the inevitable by-product of producing solid manure cakes through mechanical separation of pig slurries. This liquid fraction has negative economic value because of the high water content and the relative low contents of nutrients. Our analyses and assessments indicate that there are three possible routes for its treatment and disposal:

- (1) Direct application to nearby agricultural land;
- (2) Production of mineral concentrates through reverse osmosis, followed by direct application of the mineral concentrates to agricultural land and discharge of the by-product (water) to surface waters (or to agricultural land);
- (3) Production of inorganic fertilizers (e.g., struvite), followed by direct application of the effluent to agricultural land or discharge to and purification at a WWTP.

5.3.1 Direct application to nearby agricultural land

The cheapest disposal pathway for the liquid fraction is its application to agricultural land as organic fertilizer (manure). The liquid fraction may be considered as a nitrogen-potassium fertilizer, although it often contains also appreciable amounts of P, sulphur and some other nutritious elements. Application limits will relate to the application limits of N and P (from animal manure). However, most pig farmers do not have the agricultural land for direct disposal. Hence, these farmers have to find other disposal pathways.

5.3.2 Production of mineral concentrates through reverse osmosis

Transport and disposal of the liquid fraction at other farms is relatively expensive, because of the high water content and relatively low nutrient contents. Ultra-filtration and reverse osmosis is then a possible treatment pathway for separating water from the solids and solutes. The resulting water can be discharged either to the surface water, sewage system or agricultural land without much costs. The resulting concentrated solutes can be transported and applied directly to agricultural land of other farms. This route is extensively researched within the pilot project 'Mineral concentrates' (Velthof et al, 2010).

5.3.3 Production of struvite and purification of the effluent at a WWTP

When the two previous disposal pathways for liquid manure fractions are not feasible, the remaining pathway is its further treatment followed by the purification of the effluent at a WWTP. The (pre-)treatment has to remove the organic compounds, ammonium and phosphates as much as possible, because these are most expensive to treat at a WWTP. Hence, the pre-treatment of the liquid manure fraction involves ultra-filtration to remove residual solids and organic compounds and precipitation reactions to remove ammonium and phosphate as struvite. The effluent will have to be treated further at a WWTP, before disposal to surface waters.

Alternatively, the liquid fraction is treated by adding calcium hydroxides to recover phosphate as calcium phosphates and to recover the stripped NH_3/NH_4 in sulphuric acid (see Chapter 2). The precipitates of calcium phosphate may be added to the wet manure cake, while struvite and ammonium sulphate may be delivered to fertilizer industries for further processing and upgrading to NP fertilizers. We estimate that the net costs of the P and NH_3/NH_4 recovery through precipitation or stripping is close to zero, when the required acid and base are delivered by the fertilizer industry and the precipitates and ammonium sulphate solution can be returned to the fertilizer industry. However, the total costs of this disposal pathway is relatively large.

5.4 Assessment of the economic cost of pig slurry treatment

The different treatment options for recovering P from pig slurry are summarized in Table 9, in terms of their advantages and disadvantages and estimated economic costs. The economic cost of the treatment options has to be evaluated also relative to the intrinsic value of pig slurry. We estimated the intrinsic value on the basis of the content of nutrient elements and current market prices for organic matter, N, P and K. The value of organic matter was derived from the current value of energy. We estimate that the intrinsic value of pig slurries ranges from 6 to 11 Euro per m^3 pig slurry. This range is possible a lower estimate, as the value of other nutrient elements (S, Ca, Mg, Cu, Zn, etc.) was not included. Also the often claimed 'added value' of animal manure applied to land was not included.

In order to separate the valuable elements from pig manure for commercial purposes, costs have to be made, which depend on the route of manure processing. The net cost to produce P-rich ashes and biochars for industries ranges between 24 and 31 Euro per m^3 pig slurry. Also for the export of dried manure such costs have to be made. Significant fractions of the costs are related to the transport, treatment and disposal of the liquid manure fraction and to the drying of the solid fraction. In case the liquid fraction can be disposed off on nearby agricultural land and cheap 'waste' heat is available for the drying of the solid manure cakes, the net cost is much lower.

The costs for pig slurry processing are mainly determined by mechanical separation (2-5 Euro per m^3 pig slurry), the transport of the pig slurry fractions (6-8 Euro per m^3 pig slurry), the drying of the solid fraction (5-8 Euro per m^3 pig slurry) and the possible treatment of the liquid fraction (about 11-14 Euro per m^3 pig slurry). The treatment of the liquid fraction is needed when direct application to agricultural land is no

alternative. The uncertainties in these estimates are relatively large, due to the large variations in possible conditions in practice.

Clearly, the net economic costs of the treatment pathways for the solid manure cakes do not differ much, while the consequences and implications for the different routes are large. Please note that all disposal pathways of the solid manure refer to export of the final product to other countries. Disposal of the solid manure country on agricultural land in the Netherlands is cheaper than the disposal pathways listed in Table 9, but we presume that disposal in the Netherlands will not be possible.

Evidently, disposal of the liquid manure fraction on nearby agricultural land is by far the cheapest disposal pathway (Table 9). However, when this is not feasible, there are two remaining options and these have rather similar costs. Tables 9 and 10 make also clear that the costs of treatment of the solid and liquid manure fractions are rather similar. When combined (worse case situation), the total net cost of the transport, treatment and disposal of pig slurry are in the range of 24-31 Euro per m³ pig slurry.

Table 9

Overview of options to recover P from solid manure fractions.

	Export of dried manure	Inorganic phosphate fertilizer	Elementary P production	P biochar
Advantages/disadvantages				
- technique	simple	more complex	more complex	complex
- scale	regional	central	central	central
- market	dynamic / uncertain	stable and easily available	stable and easily available	still small / new market
- quality of the product	well known	uncertain	uncertain	unknown
- amount of material for testing projects (ton P ₂ O ₅)	<10	10-20	1000-5000	10-20
Net costs (€ per ton fattening pig slurry)				
- separation	2-5	2-5	2-5	2-5
- drying without residual heat	5-8	5-8	5-8	5-8
- drying with residual heat	<1	<1	<1	<1
- transport of dried manure	ca. 1	ca. 1	ca. 1	ca. 1
- incineration with energy production	non	-2.5 to -0.5	-2.5 to -0.5	non
- pyrolysis (no energy production)	non	non	non	0
- solution for liquid fraction needed (see below)	<1 to 14	<1 to 14	<1 to 14	<1 to 14

Table 10*Overview of options to recover P from liquid manure fractions.*

	Application on agr. land	Mineral concentrates	Pre-treatment (N-stripping, P precipitates)
Advantages/disadvantages			
- technique	simple	complex	complex
- scale	farm	farm	regional
- market	not sufficient	unknown	unknown
- quality of the product	well known	uncertain	unknown
- test projects	not needed	testing phase in practice now	tests needed
Net costs (€ per ton fattening pig slurry)	*)	**)	11-14

*) Low; not determined in this study; depends mainly on acceptance of liquid fraction by farmers and transport distance.

**) Not yet reported by the project mineral concentrates.

5.5 Conclusions

- In the Netherlands, an increasing amount of animal manure cannot be applied on the farm where it was produced. The surplus, expressed in terms of manure nitrogen and phosphorus, has to be transported to other farms and increasingly to other countries.
- There is an increasing need for manure treatment and export of resulting treatment products, because the room for application of nitrogen and phosphorus from animal manure will be further restricted during next years, while the export of untreated manure faces limits.
- Lowering the nitrogen and phosphorus contents of animal manure through adjusted animal feeding strategies is the cheapest option to lower the pressure on the manure market. However, this option will be insufficient to decrease the amounts of manure N and P to a level where all manure can be disposed off on agricultural land in the Netherlands.
- Forecasts suggest that the total number of cattle, pigs and poultry (the dominant farm animals in the Netherlands) will not decrease much. In contrast, there are market signals suggesting that the total number of animals and hence the total manure production will increase.
- The need and options for manure treatment differ between poultry farms, pig farms and (dairy) cattle. While poultry farms can dry and export the dried poultry manure relatively easily, and (dairy) cattle farms can apply most of the produced cattle slurry on own farm land, most pig farms have neither land for direct disposal nor energy and heat to dry and export pig slurries. Hence, the need for transport, treatment and export of pig slurry is by far the largest.
- Low-tech and farm-scale slurry separation techniques, with or without anaerobic digestion for biogas production, may contribute to precision manuring and thereby to lowering the cost of manure transport and disposal for some individual livestock farms. This holds especially for (dairy) cattle and pig farms, with nearby land for disposal of the liquid and solid fractions. However, the prospects of low-tech, farm-scale slurry separation techniques are insufficient to significantly relieve the pressure on the manure market for the near future.
- High-tech and large-scale manure treatment can drastically relieve the pressure on the manure market. There are various options for large-scale manure treatment and nutrient recovery, which vary in treatment pathway and final products, but not so much in the total net economic costs. These options may remove all of the surplus manure from the market, i.e., more than 20 or 40 million kg P₂O₅ per year.
- All large-scale pig slurry treatment procedures start with the mechanical separation of the liquid fraction from the solid fraction, with or without anaerobic digestion for biogas production. Anaerobic digestion has the advantage of generating biogas, while it may also facilitate the further treatment of the liquid fraction.

- The solid fraction can be treated further to produce either (i) dry organic fertilizers, (ii) mineral P fertilizers, (iii) elemental P for the food and feed industries, and (iv) biochar, to be used for soil amelioration. Each of these treatment pathways and resulting products has certain advantages and disadvantages, but the net economic costs seem not much different (Table 9).
- There is a risk that the liquid fraction is 'neglected', because it contains less valuable compounds. However, an integral solution for the surplus manure requires that the solid and liquid fractions are both disposed off in appropriate ways.
- The liquid fraction can be disposed off either through (i) direct application to agricultural land, (ii) further treatment via ultra-filtration and reverse osmosis, with direct application of the mineral concentrates on agricultural land and the direct discharge of the by-product water to the surface waters, sewage system or nearby agricultural land, and (iii) further treatment via ultra-filtration and precipitation of struvite or calcium phosphates and further purification of the effluent at a Waste Water Treatment Plant (WWTP).
- The net total economic costs of large-scale pig slurry treatment procedures similar or slightly higher than the costs of pig slurry disposal in 2009-2010.
- The costs for pig slurry processing are mainly determined by separation (2-5 Euro per m³ pig slurry), the transport of the pig slurry fractions (6-8 Euro per m³ pig slurry), the optional drying of the solid fraction (5-8 Euro per m³ pig slurry) and the possible treatment of the liquid fraction (about 11-14 Euro per m³ pig slurry). The treatment of the liquid fraction is needed when direct application to agricultural land is no option. The costs/benefits of incineration and energy recovery of dried manure cake are about 1-2 Euro per m³ pig slurry. In case (not dried) wet manure cake is incinerated, there are no cost/benefits and the costs are approx. 10 Euro per m³ pig slurry. The uncertainties in these estimates are relatively large, due to the large variations in possible conditions in practice.
- Through the manure processing techniques seem well-developed and mature, various pig slurry treatment options require further testing at pilot scale, to test the practical feasibility and to decrease the uncertainty range of the cost estimates.
- The organizational and institutional aspects related to large-scale pig slurry processing are complex and require great organizational and entrepreneurial skill. The entrepreneurial skill is there, as evidenced by the developments of many livestock farms, including those involved in the 'pilot project mineral concentrates'. The phosphorus industries also show great interest in accepting the ashes from incinerated manure cakes. Yet, bringing the interests of individual farmers, industries and intermediaries (manure processing technology companies, transporters, waste heat supplying power plants and industries) together remains a challenge.

5.6 Recommendations

- The various treatment options and pathways identified in this study and summarized in Table 9 should be discussed in-depth and subsequently prioritized by stakeholders.
- Prioritized manure treatment pathways and options should be tested at pilot scale to test the practical feasibility and to decrease the uncertainty range of the cost estimates.
- Mechanical separation of pig slurry in solid and liquid fractions is a low-cost, no-regret treatment strategy that increases the flexibility of manure disposal. It is recommended to stimulate the implementation of this treatment in practice, also to gain further experience and to improve its performance and thereby to lower the costs.

- Drying of the solid manure cakes requires external heat, which is costly when produced from fossil energy. However, when available at certain power plants and industries, the costs of drying are greatly reduced. These possibilities should be explored further.
- The treatment and disposal of the liquid fraction is relatively costly. By far, the cheapest option is its direct disposal on nearby agricultural land. Priority must be given to this disposal pathway, also through increasing its comparative advantage relative to mineral fertilizer N and K.
- The mean costs and the uncertainty ranges in the cost estimates can be decreased through targeted research, where possible together with stakeholders.

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Websites

www.moroccousafta.com/tradedata.htm

<http://phosphorusfutures.net/links>

www.bmcmoerdijk.nl/

Appendix 1 Description of different routes to recover P

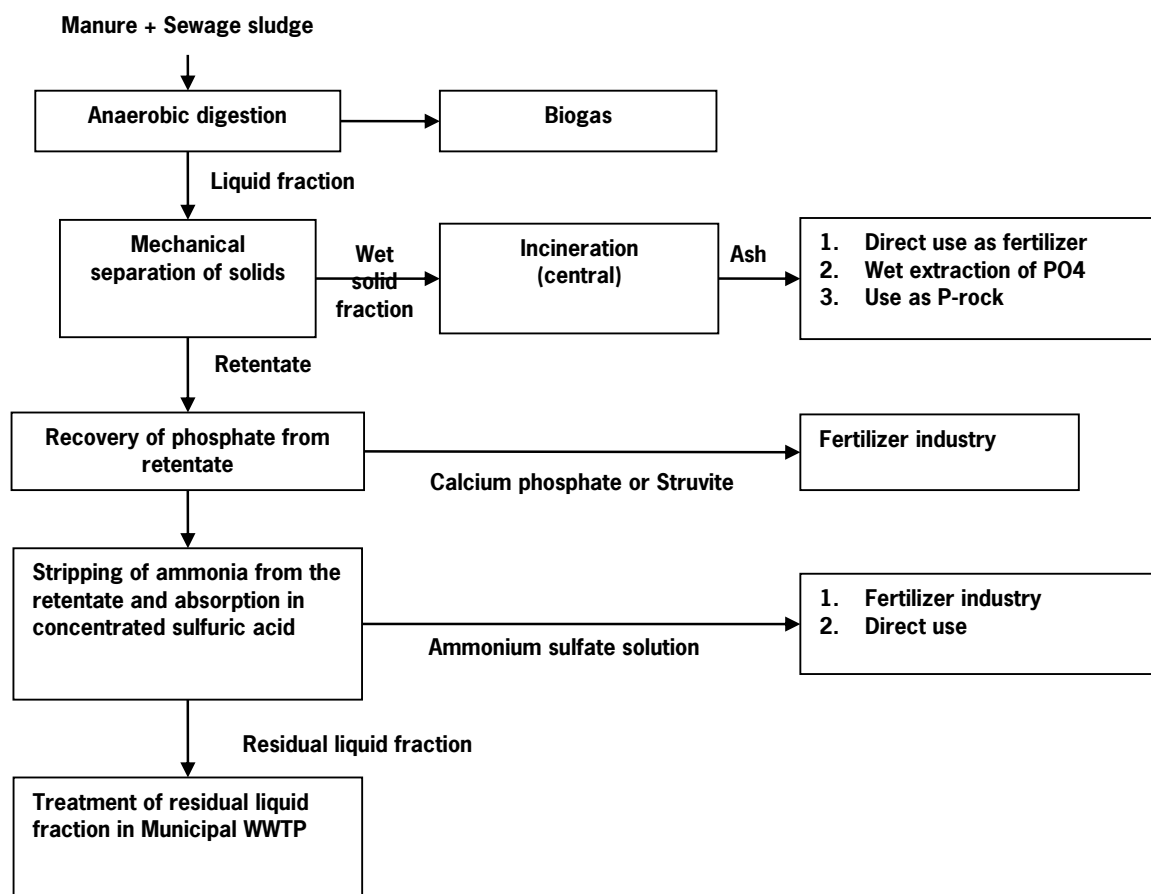
A1-1 Route 1: Scenarios 1a, 1b

Complete treatment at WWTP.

Scenario 1a

Treatment of manure at Municipal WWTP together with the treatment of sewage sludge.

The wet cake (sludge and manure) is transported to an incinerator.



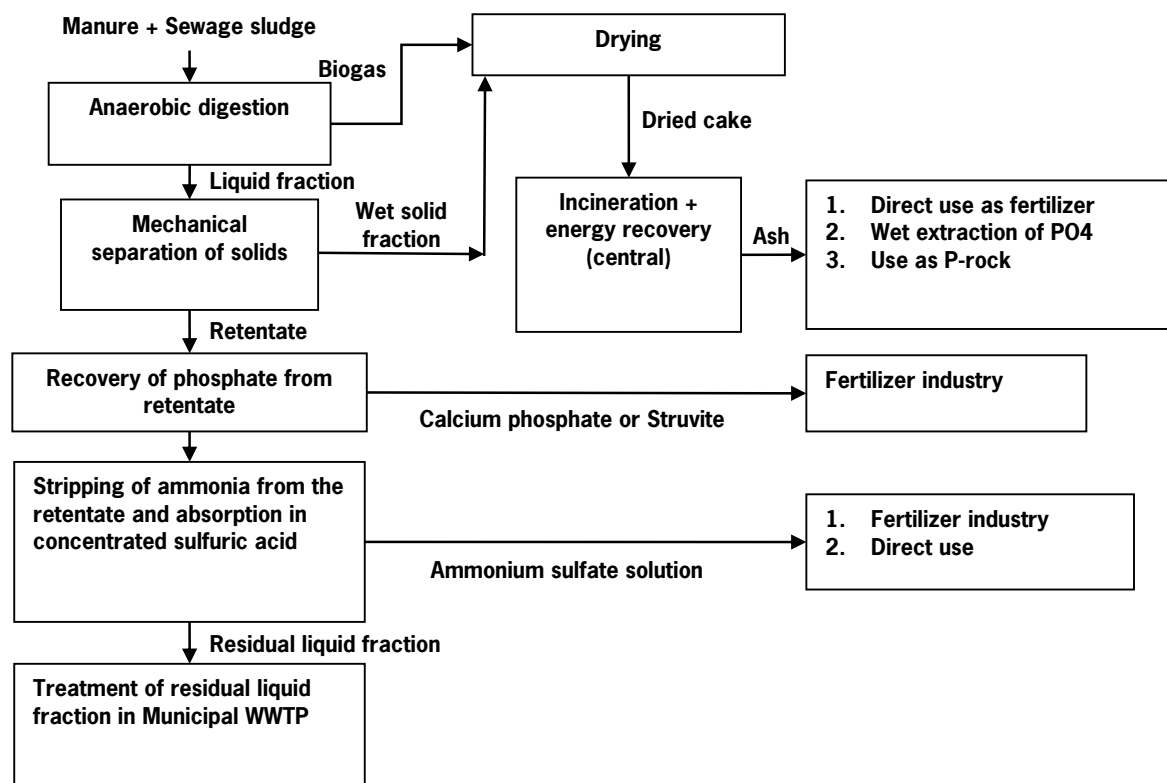
Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	1			4
NH ₃	Kg	6	1	5		5		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				2
Organics	Kg	70	60	10				

Scenario 1b

Treatment of manure at Municipal WWTP together with the treatment of sewage sludge.

The wet cake (sludge and manure) is dried (energy recovery) and transported to an incinerator.



Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	1			4
NH ₃	Kg	6	1	5		5		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				2
Organics	Kg	70	60	10				

Comparison scenario 1a	Comparison scenario 1b
<ul style="list-style-type: none"> - Treatment of manure on a WWTP together with the treatment of sewage sludge - The wet cake is transported (sewage sludge and manure) to an incinerator such as SNB - P_2O_5 remains in the ash 	<ul style="list-style-type: none"> - Treatment of manure on a WWTP together with the treatment of sewage sludge - The wet cake is transported (sewage sludge and manure) to an incinerator + energy recovery - P_2O_5 remains in the ash
<p>1. Biogas production</p> <p>Two options:</p> <ul style="list-style-type: none"> - Separated digestion - Collective digestion 	<p>1. Biogas production</p> <p>Two options:</p> <ul style="list-style-type: none"> - Separated digestion - Collective digestion
<p>Biogas can be useful on the WWTP</p> <ul style="list-style-type: none"> - CHP - Market for residual heat and CO_2 in crop farmin 	<p>Biogas can be useful on the WWTP</p> <ul style="list-style-type: none"> - CHP - Market for residual heat and CO_2 in crop farming - Drying of the wet cake
<p>2. Mechanical separation</p> <p>Two fractions can be obtained:</p> <ul style="list-style-type: none"> - Retentate (liquid fraction) - Wet cake (contains relatively large amount of P from manure) <p>Large number of modifications of the separation process</p>	<p>2. Mechanical separation</p> <p>Two fractions can be obtained:</p> <ul style="list-style-type: none"> - Retentate (liquid fraction) - Wet cake (contains relatively large amount of P from manure) <p>Large number of modifications of the separation process</p>
<p>3. Recovery of PO_4 as Calcium phosphate or Struvite.</p> <p>Can also be added to the wet cake which is transported to the incinerator</p>	<p>3. Recovery of PO_4 as Calcium phosphate or Struvite.</p> <p>Can also be added to the wet cake which is transported to the incinerator</p>
<p>4. Removal of NH_3.</p> <p>Two options:</p> <ul style="list-style-type: none"> - Recovery by stripping of ammonia from retentate and absorption in concentrated sulphuric acid - Biological conversion of NH_3 into atmospheric 	<p>4. Removal of NH_3.</p> <p>Two options:</p> <ul style="list-style-type: none"> - Recovery by stripping of ammonia from retentate and absorption in concentrated sulphuric acid - Biological conversion of NH_3 into atmospheric N
<p>5. Further treatment of the residual liquid fraction in Municipal WWTP</p>	<p>5. Further treatment of the residual liquid fraction in Municipal WWTP</p>
<p>6. Transport wet cake to the central incinerator such as SNB</p>	<p>6. Transport wet cake to the central incinerator + energy recovery</p>
	<p>7. Scenario 1b is more environmentally sustainable compared to scenario 1a (better use energy content of the organic solids in the manure)</p>
<p>Products</p> <ul style="list-style-type: none"> - Ash - Calcium phosphate - Struvite - Ammonium sulfate solution 	<p>Products</p> <ul style="list-style-type: none"> - Ash - Calcium phosphate - Struvite - Ammonium sulfate solution

Comments on route 1a and 1b.

Route 1a

- CHP on a WWTP seems promising because anaerobic digestion of sewage sludge together with manure cake produces more biogas than anaerobic digestion of sewage sludge only, and improves the opportunity to generate electricity.
- More biogas can be produced after a preliminary treatment of manure and sewage sludge. This generates more energy and a smaller amount of cake for transportation to the incinerator.
- Anaerobic digestion of manure and sewage sludge can be done separately, which has advantages and disadvantages.
- Processing on WWTP seems feasible.
- Wet cake can only be incinerated centrally.
- The costs for incineration of the wet cake are the main problem.
- The energy potential of manure and the benefits of the energy will not be fully utilised.
- Anaerobic digestion causes conversion of organic Nitrogen into NH_3 .
- Mass balances are based on manure data, sewage sludge is not included.

Route 1b

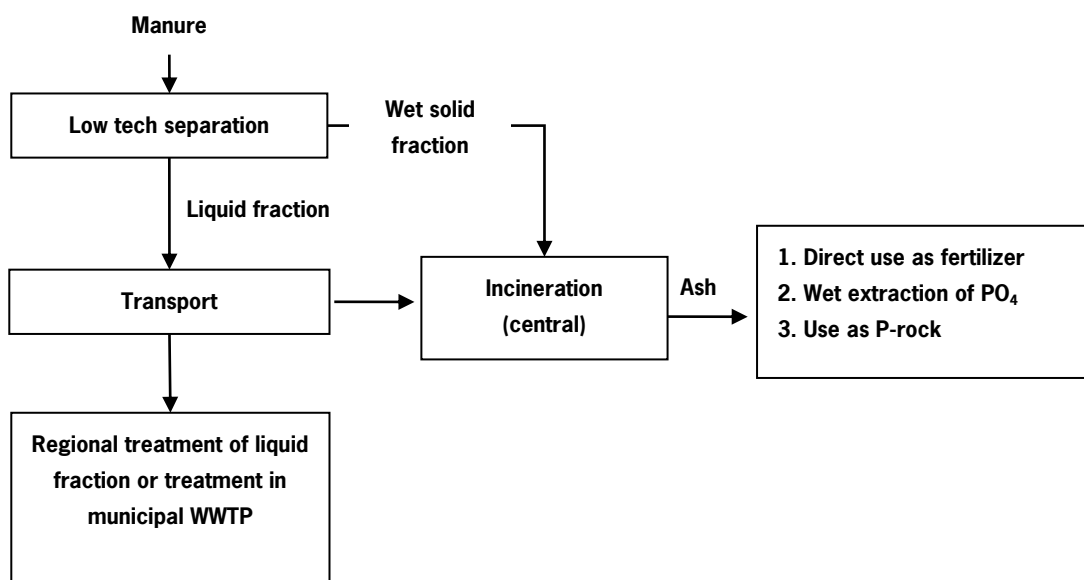
- CHP on a WWTP seems promising because anaerobic digestion of sewage sludge together with manure cake produces more biogas than anaerobic digestion of sewage sludge only, which may offer an improved opportunity for the generation of electricity. Moreover, the residual heat can be used for the drying process.
- More biogas can produce after a preliminary pre-treatment of manure and sewage sludge. This generates more energy (as biogas) and a smaller amount of cake for transportation to the incinerator.
- Anaerobic digestion of manure and sewage sludge can be done separately, which has advantages and disadvantages.
- Processing on WWTP seems feasible.
- Dry cake can only be incinerated centrally.
- The costs for incineration of the dry cake in a stand alone facility are the main problem.
- The energy potential of manure and the benefits of the energy will not be fully utilised.
- Anaerobic digestion causes conversion of organic Nitrogen into NH_3 which will enter to the water phase and consequently in the wet liquid fraction.
- Mass balances are based on manure data, sewage sludge is not included.
- Compared to route 1a, route 1b is environmentally more sustainable but also more expensive.

A1-2 Route 2: Scenario 2a, 2b, 2c

Separation at farm scale, liquid fraction will be processed in the region and wet cake will be processed at a central scale (FOCUS). See also scenarios of Route 1 (mainly wet cake) and Route 6 (mainly liquid fraction).

Scenario 2a

Separation on farm scale + regional treatment of liquid fraction + incineration of wet solid cake in incineration plant.



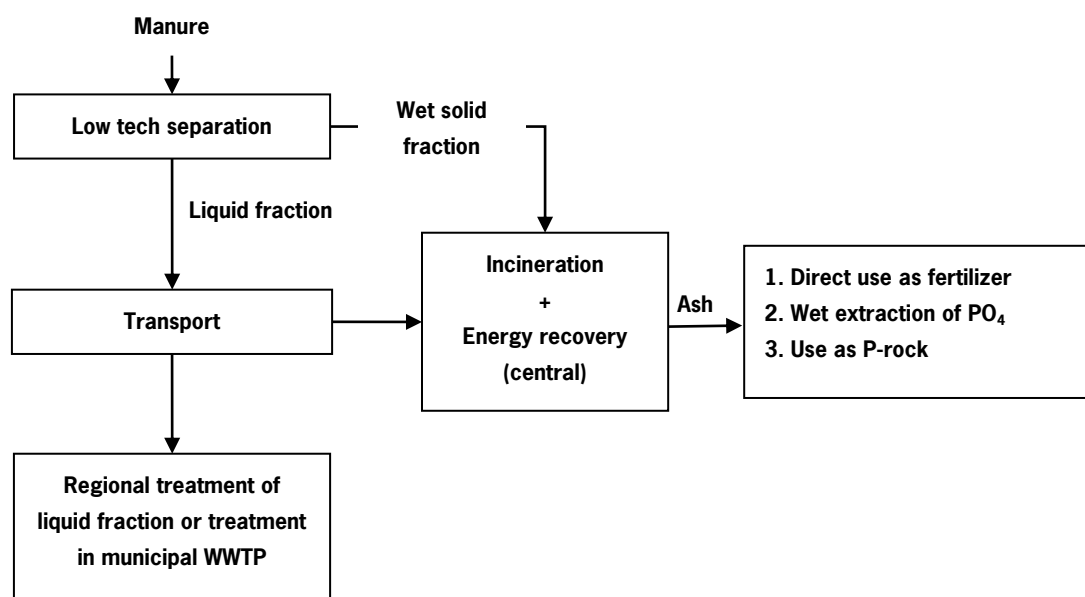
Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	(1)			4
NH ₃	Kg	6	1	5		(5)		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				(2)
Organics	Kg	70	60	10				

Between () is optional, depends on treatment route of the liquid fraction.

Scenario 2b

Separation on farm scale + incineration of wet solid cake in incineration plant + energy recovery.



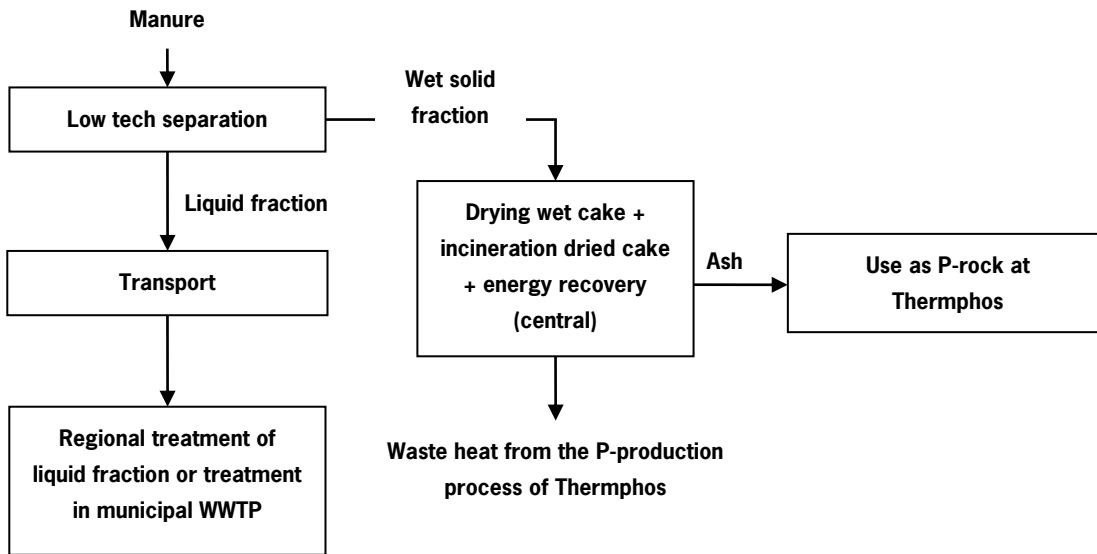
Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	(1)			4
NH ₃	Kg	6	1	5		(5)		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				(2)
Organics	Kg	70	60	10				

Between () is optional, depends on treatment route of the liquid fraction.

Scenario 2c

Separation on farm scale + incineration of wet solid cake in incineration plant + energy recovery at THERMPHOS.



Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	(1)			4
NH ₃	Kg	6	1	5		(5)		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				(2)
Organics	Kg	70	60	10				

Between () is optional, depends on treatment route of the liquid fraction.

Comparison scenario 2a	Comparison scenario 2b
<p>Mechanical separation at farm scale</p> <p>Incineration wet cake (at SNB)</p> <p>Useful recycling of ash</p> <p>Treatment liquid fraction regional or on WWTP</p>	<p>Mechanical separation at farm scale</p> <p>Incineration wet cake and energy recovery Useful recycling of ash</p> <p>Treatment liquid fraction regional or on WWTP</p>
<p>1. Mechanical separation at farm scale</p> <p>Three options:</p> <ul style="list-style-type: none"> - Low-tech (cheap, large percentage of dry matter in solid cake, colloidal particles in separated liquid fraction) - High-tech (expensive, relatively high percentage of water in the solid cake, small amount of colloidal particles in the liquid fraction) - Medium-tech 	<p>1. Mechanical separation at farm scale</p> <p>Three options:</p> <ul style="list-style-type: none"> - Low-tech (cheap, large percentage of dry matter in solid cake, colloidal particles in separated liquid fraction) - High-tech (expensive, relatively high percentage of water in the solid cake, small amount of colloidal particles in the liquid fraction) - Medium-tech
<p>2. Transport wet cake to central incinerator like SNB</p>	<p>2. Transport wet cake to central incinerator + energy recovery</p>
<p>3. Further treatment ash</p>	<p>3. Further treatment ash</p>
<p>4. Further treatment of liquid fraction regionally or on WWTP</p>	<p>4. Further treatment of liquid fraction regionally or on WWTP</p>
<p>Products</p> <ul style="list-style-type: none"> - Ash 	<p>Products</p> <ul style="list-style-type: none"> - Ash - Energy

Comparison scenario 2c

Mechanical separation at farm scale

Drying of wet cake + incineration of wet cake + energy recovery at Thermphos + functional use of residual heat of the P-production process at Thermphos Treatment liquid fraction regionally or on WWTP

1. Mechanical separation at farm scale

Three options:

- Low-tech (cheap, large percentage of dry matter in solid cake, colloidal particles in separated liquid fraction)
- High-tech (expensive, relatively high percentage of water in the solid cake, small amount of colloidal particles in the liquid fraction)
- Medium-tech

2. Transport wet cake to central incinerator + energy recovery

3. Further treatment ash

4. Further treatment of liquid fraction regional or on WWTP

Products

- Ash
 - Energy
-

Comments on route 2a, 2b and 2c.

- Assuming that separation of pig slurry at farm scale and the liquid and solid fraction are processed externally, the intensity of the separation process will probably have a limited impact on the economical feasibility of manure treatment and P-recovery.
- Low-tech separation: further treatment of the cake can be made profitable; treatment of the liquid phase is more difficult due to the amount of residual colloidal particles in the liquid phase.
- High-tech separation: further treatment of the liquid fraction can be made profitable; treatment of the manure cake is more difficult due to the high water percentage.

A1-3 Route 3: Scenario 3a, 3b, 3c

Manure is processed partly in the region and at central level.

The distinctive characteristic of route 3 is the transport of the pig slurry for partly **treatment on a regional scale and partly treatment at central level.**

- Treatment on a regional scale includes the mechanical separation of manure into a wet solid cake and a liquid fraction.
- The liquid phase is further treated at regional scale.
- Wet solid cake is treated at central scale (including direct sale of the wet fraction to crop farmers is also an option).
- Drying of the wet solid fraction on a regional scale and central further treatment of the dried cake elsewhere.

Drying of the wet solid fraction on a regional scale can be made feasible if regionally biogas is produced from the manure by anaerobic digestion.

Scenario 3a

Separation on regional scale + treatment of liquid fraction on regional scale + central treatment of wet solid fraction.

This route can be compared to the routes which are based on separation at farm scale, followed by treatment of the wet solid fraction and treatment of the liquid fraction by means of the various routes such as routes mentioned at 1 and 6.

Treatment of the liquid fraction:

- Treatment entirely at WWTP (see also route 6a).
- Partial treatment in a separate installation, additional treatment liquid fraction on WWTP (see also route 6b).
- Treatment in a separate installation and discharge of clean water on surface water (see also route 6c).

Treatment of the wet solid fraction:

- Incineration in combination with sewage slurry (centrally at SNB) and further treatment of the ash (see route 1a).
- Drying and incineration with energy recovery in a separate (central) installation and further treatment of the ash (route 1a).
- Drying and incineration with energy recovery in a separate installation at Thermphos by means of residual heat from the drying process (route 1c).

Advantage of separation on a regional scale:

- Separation can be optimized: low-tech, medium-tech, high-tech.
- Large scale treatment lowers costs.

Effect on costs: minimal, compared to similar separation routes at farm scale.

Scenario 3b

Anaerobic treatment and separation of the manure on a regional scale + further treatment of liquid fraction on regional scale + treatment of wet solid fraction elsewhere.

The distinctive characteristic of route 3a is the advantage of energy recovery in the form of biogas.

Other advantages:

- Generation of electricity from the biogas.
- ??
- Facilitates better separation.
- Less organic matter in the wet manure cake.
- Less organic Nitrogen in the wet solid manure cake.
- Liquid fraction is more easy to process.

Scenario 3c

Anaerobic treatment and separation on regional scale + further treatment of liquid fraction on regional scale + drying wet solid fraction on regional scale + central al treatment of the dry solid cake.

The advantage of scenario 3c over scenario 3b is the production of the residual heat in the CHP, which can be used to dry the wet cake. The dried solid fraction can be processed further:

- Incineration with energy recovery in a central installation (see also scenario 1c).
- Pyrolysis for the production of P-biochar (see scenario 5). This scenario may lower the net costs of scenario 5 for the production of P-biochar.

A mechanical, physical or thermal pre-treatment before the anaerobic fermentation may increase the production of biogas and energy.

A1-4 Route 4 Scenario 4a en 4b

Separation at farm scale, in combination with production of biogas at farm scale + optional drying of the wet solid cake with residual heat.

Scenario 4a

Anaerobic digestion on farm scale + Separation on farm scale + Drying of wet solid fraction on farm scale + Regional treatment of liquid fraction.

The advantage of route 4 is the production of biogas which can be used for the generation of electricity at farm scale via CHP. Moreover, the residual heat from this process can be used to dry the wet solid fraction. The liquid fraction can be processed regionally. The dry solid fraction can be processed centrally (see route 1).

However, for the time being, this scenario is considered to be unfeasible, both technically and economically. At this moment, due to the complexity of the drying process, and the small scale of the anaerobic digestion process only a comparatively small volume of biogas can be produced from the manure.

The drying process is optional and can be left out to simplify manure treatment at farm scale. The wet cake can be processed centrally (see route 1).

Rising energy prices and even rising costs of P-ore may possibly encourages this scenario in the future.

Scenario 4b

Anaerobic Co-digestion on farm scale + Separation on farm scale + Drying of wet solid fraction on farm scale + Regional treatment of liquid fraction.

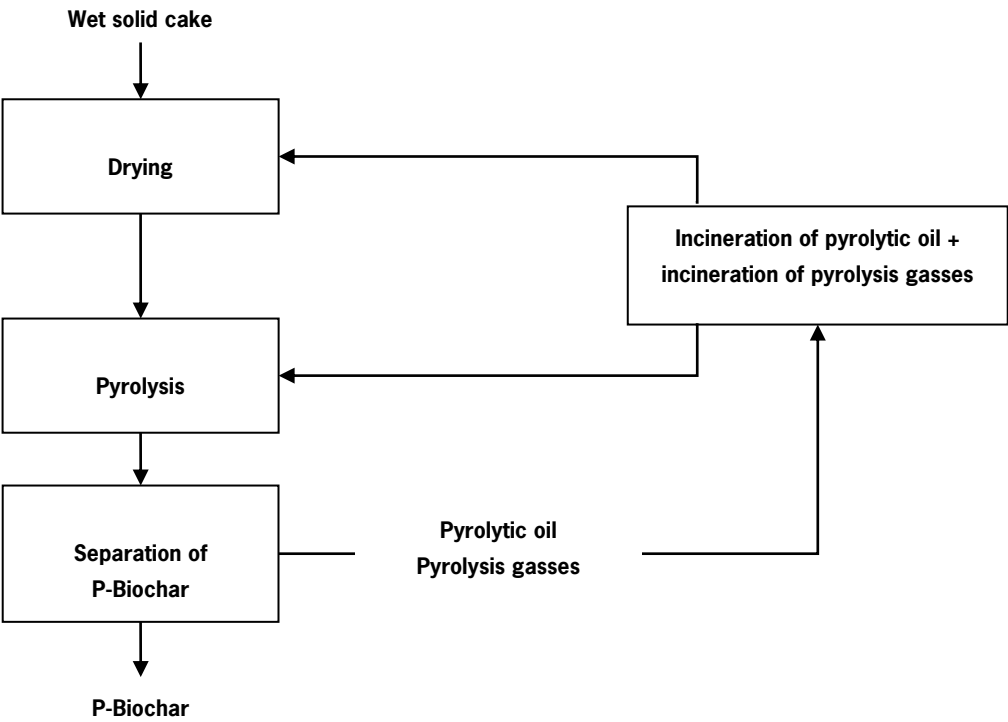
Route 4b has the same advantage as route 4a. The additional advantage of this route is the production of biogas which can be used for the generation of electricity on farm scale via CHP. The residual heat from this process can be used for drying the wet solid fraction. The liquid fraction can be processed regionally. The dry solid fraction can be processed centrally (see route 1).

Scenario 4b is considered to be more feasible than Scenario 4a, because:

- A larger quantity of biogas can be produced.
- Central treatment of the wet cake and regional treatment of the liquid fraction result in a process from which the end products are no longer regarded as manure.

A1-5 Route 5 (Scenario 5)

Production of P-biochar from wet solid cake by means of pyrolysis.



Comparison scenario 5

Mechanical separation at farm scale
Transport wet cake to pyrolysis installation
Transport liquid fraction to regional

1. Drying of the manure cake
 2. Pyrolysis of the dry manure cake
which produces the following fractions:
 - P-biochar
 - Pyrolytic oil
 - Pyrolysis gasses
 3. Separation of P-biochar
 4. Incineration of pyrolytic oil and pyrolysis gasses. Use of
energy (heat) for the pyrolytic process
 5. Products
 - P-biochar
-

A1-6 Route 6 Scenario 6a, 6b, 6c, 6c- alternative

Separation on farm scale and regional treatment of the liquid fraction (FOCUS).

Route 6 focuses on the mechanical separation on farm scale of pig slurry into a liquid fraction and a wet solid cake. In scenarios 6a, 6b, 6c and 6c- the following assumptions are taken into account:

There are no technically or economically feasible methods available on farm scale for further treatment of the (wet) solid cake and the liquid fraction.

- The solid fraction has to be transported for external treatment or sale on the agricultural market.
- The liquid fraction cannot be sold on the agricultural market.
- The liquid fraction will have to be treated regionally.
- The amount of P in the liquid fraction is minimal compared to the amount of P in the manure cake.

These assumptions lead to the conclusion that a cost-effective treatment of the liquid fraction is of primary importance for the economic recovery of P_2O_5 or PO_4 from the solid fraction. The recovery of PO_4 from the liquid fraction is of less importance.

There are three methods for treatment of the liquid fraction

1. Scenario 6a:
Direct discharge to the sewer and further treatment at a WWTP. This requires a permit and the payment of the standard purification fees. Large scale purification at a WWTP may be considered to be cheaper than purification at a regional scale. NH_3 -recovery does not take place at a WWTP. NH_3 and PO_4 -recovery, however, may prove to be feasible in the future by means of direct methods, applied at the WWTP, or by indirect methods by means of central sludge processing.

2. Scenario 6b:

Partial treatment at regional scale is including both PO_4^- and NH_3^- recovery. The treated liquid fraction , which contains less PO_4 and NH_3 than the original liquid fraction, is discharged into the sewer and will end up at the WWTP.

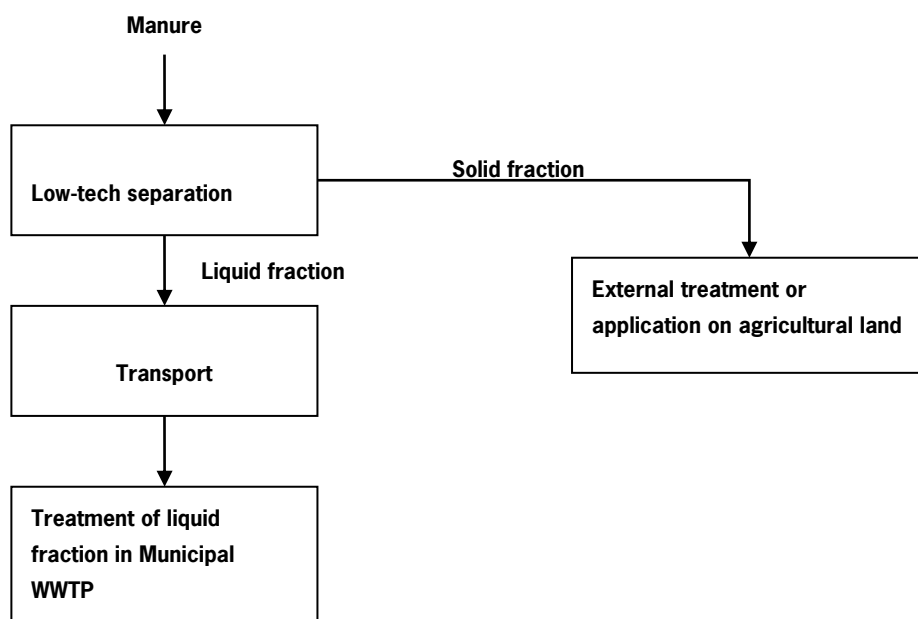
3. Scenario 6c:

Total purification of the liquid fraction at a regional scale resulting in maximal recovery of NH_3 and PO_4 and also K for useful recycling and the production of liquid waste which can be discharged to the surface water.

Mechanical separation can , in fact, produce 6 types of liquid fractions depending on whether the manure was anaerobically digested beforehand and the intensity of the separation process along high-, medium- or low-tech methods. The following diagrams show processes based on non-digested manure and low-tech separation.

Scenario 6a

Low tech separation on farm scale + Treatment of liquid fraction in WWTP.



Total amounts and/or composition (indicative values!).

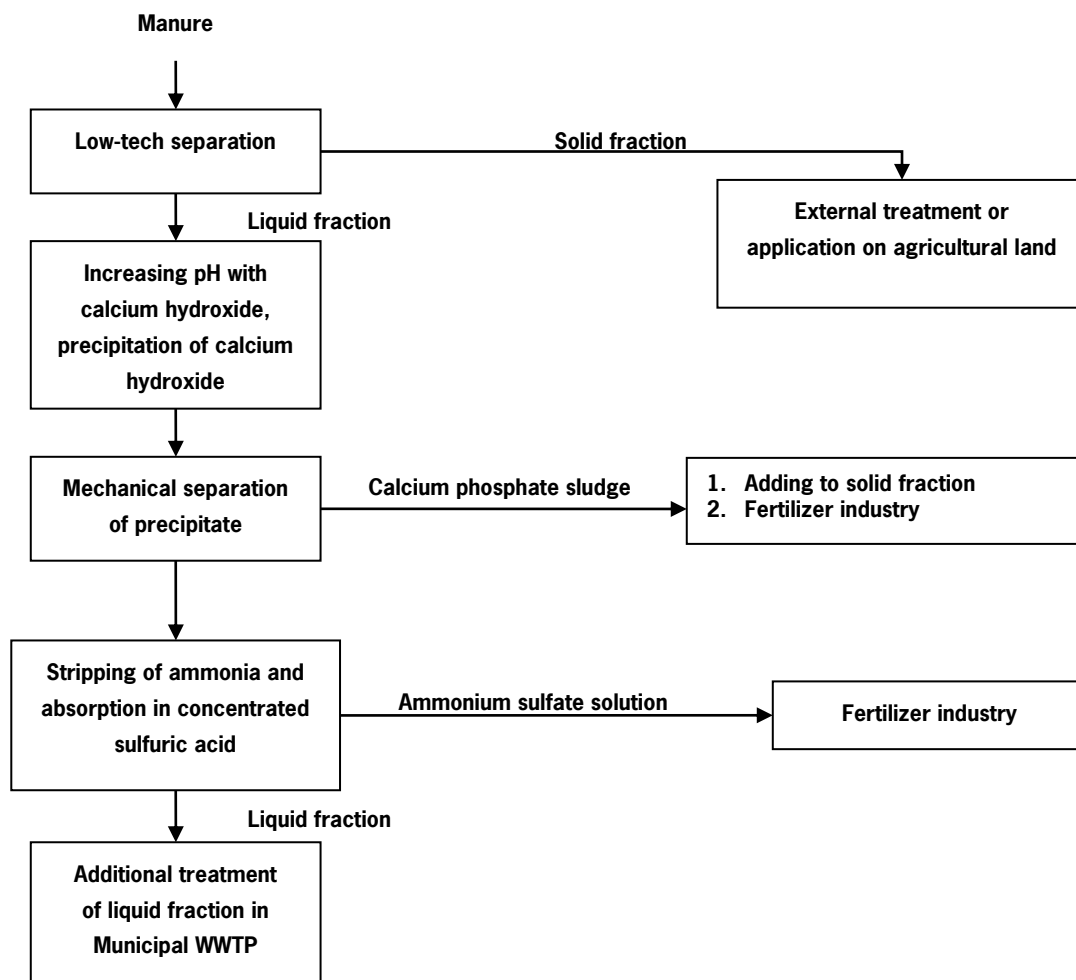
Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate (WWTP)	Ammonium sulphate solution (WWTP)	Ash (INCINERATOR)
Amount	Kg	1000	250	750 (WWTP)			
Water	Kg	900	200	700			
P ₂ O ₅	Kg	5	4	1	1		4
NH ₃	Kg	6	1	5		?	
Organic-N	Kg	8	2	0			
K ₂ O	Kg	8	2	6			
Organics	Kg	70	60	10			

P₂O₅-recovery and NH₃ (additional) from the liquid fraction at the WWTP.

P₂O₅-recovery from the ash of the incinerated manure cake.

Scenario 6b

Low tech separation on farm scale + regional treatment of liquid fraction + additional treatment of liquid fraction in WWTP.



Total amounts and/or composition (indicative values!).

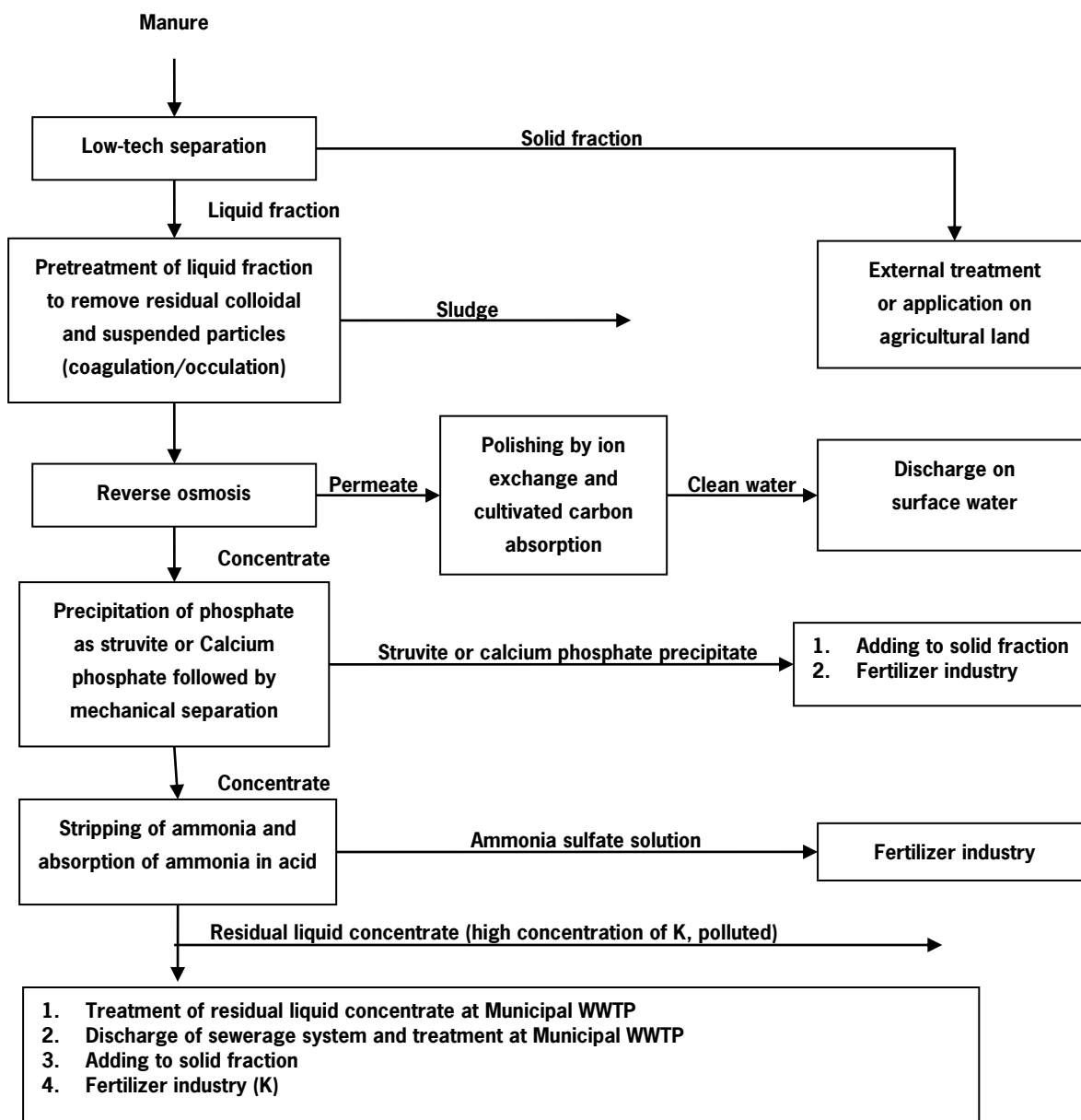
Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Liquid fraction (WWTP)	Ash
Amount	Kg	1000	250	750			750	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	1			4
NH ₃	Kg	6	1	5		5		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				
Organics	Kg	70	60	10				

P₂O₅-recovery and possible NH₃-recovery from liquid fraction at WWTP.

P₂O₅-recovery from the ash of the incinerated manure cake.

Scenario 6c

Low tech separation on farm scale + regional treatment of liquid fraction + discharge of treated liquid fraction on surface water.



Total amounts and/or composition (indicative values!).

Components	Units	Manure	Wet solid fraction	Liquid fraction	Calcium phosphate	Ammonium sulphate solution	Residual liquid fraction (WWTP)	Ash
Amount	Kg	1000	250	750			75	
Water	Kg	900	200	700				
P ₂ O ₅	Kg	5	4	1	1			4
NH ₃	Kg	6	1	5		5		
Organic-N	Kg	8	2	0				
K ₂ O	Kg	8	2	6				
Organics	Kg	70	60	10				

P₂O₅-recovery from the ash of the incinerated manure.

P₂O₅-recovery from the ash of the incinerated manure cake.

Comparison scenario 6a	Comparison scenario 6b	Comparison scenario 6c	Comparison scenario 6c
Simple mechanical separation at farm scale	Simple mechanical separation at farm scale	Simple mechanical separation at farm scale	ALTERNATIVE (different location for reverse osmosis in treatment chain) Simple mechanical separation at farm scale
Solid fraction to crop farmer or external treatment	Solid fraction to crop farmer or external treatment	Solid fraction to crop farmer or external treatment	Solid fraction to crop farmer or external treatment
Treatment liquid fraction at regional WWTP	Treatment of liquid fraction, partially regionally, partially at WWTP	Entire treatment liquid fraction in regional facility, discharge clean water on surface water	Entire treatment liquid fraction in regional facility, discharge clean water on surface water
1. Simple mechanical separation	1. Simple mechanical separation	1. Simple mechanical separation	1. Simple mechanical separation
2. Treatment liquid fraction at WWTP	2. Pre-treatment at high pH to remove residual colloidal particles and stripping of ammonia at high pH. Calcium phosphate sludge is delivered as precipitate	2. Pre-treatment liquid fraction at neutral pH to remove colloidal particles. Results in sludge	2. Pre-separation liquid fraction at high pH , for removal colloidal particles and stripping of ammonium at high pH. Calcium phosphate is delivered as precipitate
	3. Separation precipitate (Calcium phosphate)	3. Reverse osmosis liquid fraction, results in concentrate and permeate	3. Separation precipitate (Calcium phosphate)
	4. Stripping of Ammonium and absorption of ammonium in concentrated sulphuric acid	4. Treatment permeate (or disposal permeate in sewer)	4. Stripping of Ammonium and absorption of ammonium in concentrated sulphuric acid

Comparison scenario 6a	Comparison scenario 6b	Comparison scenario 6c	Comparison scenario 6c
	5. Treatment of the residual liquid fraction at WWTP	5. Treatment concentrate: struvite precipitation or calcium phosphate precipitate or calcium hydroxide precipitate (removal phosphate)	5. Neutralization stripped liquid fraction
		6. Treatment concentrate: removal residual NH_3 through stripping. Increase of pH is necessary (partially carried out in previous phase)	6. Reverse osmosis stripped liquid fraction. Results in concentrate and permeate. Possible also a small amount of precipitate
		7. Treatment small residual liquid fraction (concentrate): - on WWTP (possibly by disposal in sewer) - as an addition to the solid cake - sell to fertilizer industry because of high potassium content	7. Disposal permeate into sewer
			8. Treatment small amount of concentrate: - Low concentration of NH_3 and PO_4 - High concentration of Potassium - Treatment concentrate possibly by disposal into sewer - as an addition to the solid cake - sell to fertilizer industry because of high potassium content
Products - Wet solid cake - Liquid fraction	Products - Wet solid cake - Calcium phosphate precipitate (sludge) - Ammonium sulphate solution	Products - Wet solid cake - Calcium phosphate precipitate (sludge) - Ammonium sulphate solution - K-concentrate - Sludge	Products - Wet solid cake - Calcium phosphate precipitate (sludge) - Ammonium sulphate solution - K-concentrate - Sludge

Comments on scenario 6c

PO_4 can also be obtained from the liquid fraction as a precipitate with $\text{Al}_2(\text{SO}_4)_3$ as aluminium sulphate. A small amount of sludge with concentrated phosphate is obtained after the separation of the precipitate. This method seems to be uneconomical because the entire liquid fraction has to be treated.

Appendix 2 Treatment of wet solid manure cake

Indicative calculation of composition of relevant products, treatment costs, energy need and energy recovery.

A-2.1 Introduction

In this appendix a calculation model (in Excel) is developed that can be used to calculate briefly the composition of the various products that can be obtained from the different types of treatment scenarios of the wet solid manure cake, the energy demand, the energy recovery and the treatment costs. The specific aim of the model is to provide indicative data which can be used for a brief technical and economic evaluation of a treatment scenario. The effect of the variation of the value of the input parameters can be illustrated also (sensitivity analyses). In the calculations it is assumed that annually 20 million kg P_2O_5 have to be recovered. Because there is only limited experience with the incineration and pyrolysis of manure fractions costs figures of these treatment steps are hardly available. However, with the incineration of Organic fractions of Municipal Solid Wastes a lot of technical and economic data is available. Because the incineration value of the dry matter in Municipal Solid Waste is more or less comparable with the incineration value of the dry solid matter present in the solid manure cake cost figures available for the incineration of Municipal Solid Waste are also used for incineration of wet or dry solid manure cake. It has to be noted that notwithstanding the extended practical experience with the incineration of Municipal Solid Waste it is observed that data regarding investment and operating costs widely scatter. Information regarding investment and operating costs of the incineration of Municipal Solid Wastes can be found in Anonymus (1999, 2007, 2009), Consonni et al.(2005), Economopoulos (2010), Perkoulidis et al.(2010) and Tsilemou and Panagiotakopoulos (2006).

The structure of this appendix is as follows:

Section 1

Overview of relevant input parameters (variables), assumptions that are made and the possible variation of these input parameters.

Section 2

Equations to calculate the amount and composition of the wet solid manure cake, the dry solid manure cake, the P-biochar and the ash.

Section 3

Equations that can be used in the calculation of the costs of drying of wet solid manure cake, pyrolysis of dry solid manure cake and incineration of wet or dry solid manure cake.

Section 4

Equations that can be used in the calculation of the energy demand in the drying process and the production of electrical energy and heat from the incineration process of dry solid manure cake.

Section 5

Standard values of the input parameters used in the calculations with an Excel program.

Section 6

Results of some exploratory calculations using the Excel calculation program.

Section 7

Conclusions.

A2-2 Relevant input parameters (process variables)

x_1 = mass fraction of the original (slurry) manure that is present in the wet solid manure cake obtained at a mechanical separation process (-).

Variations: 0.15, 0.20, 0.25, 0.30.

The value of x_1 depends on the type of slurry manure, the use of coagulants and flocculants and the type of the mechanical separation process.

x_2 = dry solids content of the slurry manure (kg/ton).

Variations: 80, 100, 120 kg/ton slurry manure.

The value of x_2 depends on the type of slurry manure.

x_{2a} = fraction of dry solids, present in the slurry manure, that is concentrated in the wet solid manure cake (-).

Variations: 0.7, 0.8.

The value of x_{2a} depends on the type of slurry manure, the type of the mechanical separation process and the use of coagulants and flocculants.

x_3 = ash content of the slurry manure (kg/ton).

Variations: 20, 25, 30 kg/ton slurry manure.

The value of x_3 depends on the type of manure. The ash includes also the soluble inorganic components with exception of N-NH_3 .

x_{3a} = fraction of ash, present in the slurry manure, that is concentrated in the wet solid manure cake (-).

Variations: 0.65, 0.60, 0.55.

The value of x_{3a} depends on the type of slurry manure, the use of coagulants and flocculants and the type of the mechanical separation process.

x_4 = N-NH_3 content of the slurry manure (-).

Variations: 4, 6 kg N-NH_3 kg/ton slurry manure.

The value of x_4 depends on the type of slurry manure and the pretreatment process of the slurry manure (for example anaerobic digestion).

Assumptions:

- the concentrations of NH_3 in the wet manure cake fraction and in the liquid manure fraction are identical;
- no losses of N-NH_3 in the drying process of the wet solid manure cake;
- complete loss of N-NH_3 in the pyrolysis process of the dry or wet solid manure cake;
- complete loss of N-NH_3 in the incineration process of the dry or wet solid manure cake.

N-organic= 2 kg/ton slurry manure.

Assumptions:

- 95% of the N-organic is present in the wet solid manure cake and 5% is present in the liquid manure fraction;
- in the pyrolysis process the amount of N-organic is completely kept in the P-biochar;
- in the incineration process N-organic is completely oxidized and removed with the incineration gases;
- the presence of NH_3 in the wet solid manure cake has only a small effect on the composition of the wet solid manure cake and the treatment costs.

x_p= total amount of P_2O_5 present in the slurry manure (kg P_2O_5 /ton slurry manure).

Variations: 4, 5, 6 kg P_2O_5 /ton slurry manure.

x_{pf}= fraction of the total amount of P_2O_5 that is concentrated in the wet solid manure cake (-).

Variations: 0.70, 0.80, 0.90, 0.9.

x₅= required thermal energy for evaporation of 1 kg of water (MJ/kg).

Variations: 1.6, 2.3, 3.0 MJ/kg water.

The evaporation value of water is about 2.3 MJ/kg water. In a drying process in which no recovery of energy from the off drying gases is applied the required energy for the evaporation of water in the drying process is in the order of 1.5 times the evaporation value of water. However, in general some recovery of heat for reuse is applied. In an advanced drying system with optimized recovery of heat from the drying gasses and reuse of this heat again in the drying process it can be expected that the net amount of heat required for the drying process might be less than 2.3 MJ/kg water. However, it has to be remarked that the capital costs of an advanced drying process are higher than that of a simple drying process with no or limited recovery of energy for reuse.

x₆= combustion value (caloric value) of the dry matter (organics and inorganics) present in the wet (or dry) solid manure cake (MJ/kg): 17 MJ/kg.

The value of x₆ can vary, depended on the type of organic and inorganic material in the wet or dry solid cake and the ratio between the amount of organic and inorganic material.

x₇= efficiency of the energy production in the incineration process of dry solid manure cake (-).

Variations: 0.8, 0.9.

Energy production can be heat only or partly heat and partly electricity. The value of x₇ depends on the type of incineration process.

x₈= efficiency of the production of electricity in the incineration process of dry solid manure cake (-).

Variations: 0.25, 0.30, 0.35.

The value of x₈ can vary, depended on the type of the combined process of incineration and production of electrical energy. In general it can be expected that in case of incineration of a dry organic waste steam the value of x₈ is less than 0.4. In the calculations it is assumed that the major part of the energy produced in the combined process of incineration with production of electricity is heat or waste heat, that can be used for drying the wet solid manure cake before this cake enters the incinerator.

x9= fraction of the solid matter present in the dry solid manure cake that is converted in the pyrolysis process in gaseous components (-).

Variations: 0.3, 0.4, 0.5.

It is assumed that the pyrolysis process is applied to the dry solid manure cake. The value of x9 depends on the composition of the dry solid manure cake, the type of pyrolysis process, type of reactor and the applied process conditions: applied heating rate, applied temperature, residence time in the reactor.

x10= amount of NH_3 present in the wet solid cake fraction, obtained after mechanical separation of ton of slurry manure (kg). In the further calculations this process parameter is not considered.

x11= investment for the drying installation per ton of wet solid manure cake (Euro per ton annual treatment capacity installed).

Variations: 75, 100, 125 Euro/ton annual treatment capacity installed.

The value of x11 also depends on other external facilities that are relevant in the drying process. For example, in the vicinity of an incineration process the treated drying gases containing small amounts of odour and ammonia, can be mixed up with the incineration air that is used in the incinerator.

x12= investment for the pyrolysis installation per ton of dry solid manure cake, inclusive energy recovery for the drying of the wet manure cake (Euro per ton annual treatment capacity installed). Variations: 200, 300 Euro/ton annual treatment capacity installed.

It is assumed that the pyrolysis process is applied on the dry solid manure cake. Because a very large part of the energy content of the dry material in the dry solid manure cake is not used as an energy source, it is in general not possible to produce a net amount of energy from the pyrolysis process, unless the wet solid manure cake is dried elsewhere with the use of waste heat. It has also to be realized that the pyrolysis process itself requires energy (heat). Very probably the required amount of energy for the pyrolysis process can be obtained by incineration of the pyrolysis gasses and pyrolysis oil.

x13= investment for the incineration installation without energy recovery for treatment of wet solid manure cake (Euro per ton annual treatment capacity installed).

Variations: 200, 250 Euro/ton annual treatment capacity installed.

It is assumed that the investment for an incinerator without energy recovery is more or less in the same order as a pyrolysis installation (with incineration of the pyrolysis gasses) or somewhat lower.

x14= investment for the incineration installation with energy recovery (production of electricity) for the treatment of dry solid manure cake (Euro per annual ton treatment capacity installed).

Variations: 300, 400 Euro/ton annual treatment capacity installed.

It is assumed that the investment for an incinerator with energy recovery (production of electricity) is somewhat higher than the investment for an incinerator without energy recovery.

x15= capital costs (per ton) as fraction of the investment (per ton annual treatment capacity installed) (-)

Variations: 0.1, 0.15

x16= variable costs (per ton) as fraction of the investment (per ton annual treatment capacity installed) (-)
Variations: 0.1, 0.15, 0.2

A2-3 Calculation of the amount and composition of the wet solid manure cake, the dry solid manure cake, the p-biochar and the ash

A2-3.1 Starting points

- Concentration of P_2O_5 in the slurry manure is 5 kg per ton.
- 4 kg P_2O_5 is present in the wet solid cake, obtained after mechanical separation of 1 ton of slurry manure in a wet solid cake (solid fraction) and a liquid phase (liquid fraction).
- 1 kg P_2O_5 is present in the liquid phase (liquid fraction).
- To recover 20 million kg of P_2O_5 per year 5 million ton of slurry manure has to be treated per year.

A2-3.2 Amount and composition of the wet solid manure cake

y1= Solid matter content of wet solid manure cake (kg/ton wet solid manure cake). Solid matter contains also the $N-NH_3$ and N-organic.

$$y1 = x2 \cdot x2a / x1 \text{ (kg/ton)}$$

y2= Weight fraction of solids in the wet solid manure cake

$$y2 = y1 / 1000 \text{ (-)}$$

y3= Ash content of the wet solid manure cake (kg/ton wet solid manure cake)

$$y3 = x3 \cdot x3a / x1 \text{ (kg/ton)}$$

y4=.Organic matter content of the wet solid manure cake (kg/ton wet solid manure cake)

Organic matter content of the wet solid manure cake = solid matter content - ash content

$$y4 = y1 - y3 \text{ (kg/ton)}$$

y5= P_2O_5 content of the wet solid manure cake (kg P_2O_5 /ton wet solid manure cake)

$$y5 = x_p \cdot x_{pf} / x1 \text{ (kg/ton)}$$

y6= Amount of water per kg P_2O_5 present in the wet solid manure cake (kg water/kg P_2O_5)

$$y6 = (1000 - y1) / y5$$

y7= Amount of solids per kg P_2O_5 present in the wet solid manure cake (kg solids/kg P_2O_5)

$$y7 = y1 / y5 \text{ (kg/kg)}$$

y8= P_2O_5 content per ton of dry solid manure cake (kg P_2O_5 /ton dry manure)

$$y8 = 1000 y5 / y1 \text{ (kg/ton)}$$

y9= Amount of organics per kg P_2O_5 present in the wet solid manure cake (kg organics/kg P_2O_5)

$$y9 = y4 / y5 \text{ (kg/kg)}$$

y10= Amount of ammonia in the wet solid manure cake (kg ammonia per ton of wet solid manure cake)

$$y10 = x4 \text{ (kg/ton)}$$

A2-3.3 Amount and composition of the dry solid manure cake

Assumptions:

- In the drying process of the wet solid manure cake only the water is lost;
- The water is removed completely.

y11= Amount of ash in the dry solid manure cake per ton of dry solid manure cake (kg ash per ton of dry solid manure cake). (P_2O_5 is part of the ash)

y11= $1000 \cdot y_3 / y_1$ (kg/ton)

y12= Amount of organics in the dry solid manure cake per ton of dry solid cake (kg organics per ton of dry solid manure cake)

y12= $1000 - y_{11}$ (kg/ton)

y13= Amount of P_2O_5 per ton of dry solid manure cake (kg P_2O_5 / ton of dry solid manure cake)

y13= $1000 \cdot y_5 / y_1$ (kg/ton)

y14= Amount of solids per kg P_2O_5 present in the dry solid manure cake (kg solids/kg P_2O_5)

y14= $1000 / y_{13}$ (kg/kg)

y15= total amount of dry solid manure cake containing 20 million kg P_2O_5 (ton)

y15= $20 \cdot 10^6 / y_{13}$ (ton)

A2-3.4 Amount and composition of the p-biochar

Fraction of the solids that is converted into a gas phase and/or into a pyrolysis oil: x9 (-)

y16= Amount of solid material (P-biochar) that is produced from 1 ton of dry solid manure cake (kg P-biochar/ton dry solid manure cake)

y16= $1000 \cdot (1 - x_9)$ (kg/ton)

y17= Ash content of the P-biochar (kg ash/ ton P-biochar)

y17= $1000 \cdot y_{11} / y_{16}$ (kg/ton)

y18= Organic matter content of the P-biochar (kg organics/ton P-biochar)

y18= $1000 - y_{17}$ (kg/ton)

y19= Amount of P_2O_5 per ton of P-biochar produced (kg P_2O_5 /ton P-biochar)

y19= $1000 \cdot y_{13} / y_{16}$ (kg/ton)

y20= Amount of solids in the P-biochar per kg P_2O_5 present in the P-biochar (kg solids/kg P_2O_5)

y20= $1000 / y_{19}$ (kg/kg)

A2-3.5 Amount and composition of the ash of an incineration process

y_{21} = Amount of P_2O_5 per ton of ash (kg P_2O_5 per ton ash).

Assumption has been made that the amount of ash is equal to the amount of inorganics present in the wet solid manure cake. This means that the amount of P_2O_5 (kg) per ton of ash is given by the equation:

$$y_{21} = 1000 \cdot y_{13} / y_{11} \text{ (kg/ton)}$$

y_{22} = Amount of ash (kg) per kg P_2O_5

$$y_{22} = y_{11} / y_{13} \text{ (kg/(kg))}$$

y_{23} = Total amount of ash (ton) containing 20 million kg P_2O_5

$$y_{23} = y_{22} \cdot 20 \cdot (10^3) \text{ ton}$$

$$y_{24} = y_{24}$$

A2-3.6 Summary of the amount of products obtained from one ton of slurry manure

$y_{51} = x_1 \cdot 1000$ = Amount of wet solid manure cake produced from one ton slurry manure

$y_{52} = y_{51} \cdot y_1 / 1000$ = Amount of dry solid manure cake produced from one ton slurry manure

$y_{53} = y_{52} \cdot (1 - x_9)$ = Amount of P-biochar produced from one ton slurry manure

$y_{54} = y_{52} \cdot y_3 / 1000$ = Amount of ash produced from one ton slurry manure

A2-4 Calculation of the costs of the treatment processes

A2-4.1 Costs of drying of wet solid manure cake

Investment drying process: x_{11} Euro per ton (wet solid manure cake) annual treatment capacity installed.

Treatment costs (per ton wet solid manure cake):

- Capital costs: $x_{11} \cdot x_{15}$ Euro/ton wet solid manure cake;
- Variable costs: $x_{11} \cdot x_{16}$ Euro/ton wet solid manure cake.

y_{25} = Drying costs per ton wet solid manure cake

$$y_{25} = x_{11} \cdot (x_{15} + x_{16}) \text{ Euro/ton wet solid manure cake}$$

y_{26} = Drying costs per kg P_2O_5 present in the wet solid manure cake

$$y_{26} = y_{25} / y_5 \text{ Euro/kg } P_2O_5$$

y_{27} = Amount of energy necessary for drying of 1 ton of wet solid manure cake (MJ)

$$y_{27} = (1000 - y_1) \cdot x_5 \text{ (MJ/ton wet manure)}$$

A2-4.2 Costs of pyrolysis of wet solid manure cake

The pyrolysis process consists of two steps:

- Drying of the wet solid manure cake. Energy necessary for the drying process is partly obtained from external sources and partly from the incineration of pyrolysis gas and pyrolysis oil. It is assumed that the major part of the energy necessary for the drying process of the wet solid manure cake is supplied by a waste energy source from elsewhere. Because only about half of the organic matter is converted into pyrolysis oil and pyrolysis gases, it is assumed that there is no or a negligible net production of electrical or thermal energy or energy rich fuels. The drying of wet solid manure cake results in a decrease of the total amount of manure product that is treated in the pyrolysis process.
- Pyrolysis of dry solid manure. Energy required for the pyrolysis is obtained from the incineration of pyrolysis gas and/or pyrolysis oil.

Investment of the drying process: x_{11} Euro per ton (wet solid manure cake) annual treatment capacity installed.

Treatment costs (per ton wet solid manure cake):

- Capital costs: $x_{11} \cdot x_{15}$ Euro/ton wet solid manure cake;
- Variable costs: $x_{11} \cdot x_{16}$ Euro/ton wet solid manure cake.

Investment pyrolysis process: x_{12} Euro per annual ton (dry solid manure cake) treatment capacity installed.

Treatment costs (per ton dry solid manure cake):

- Capital costs: $x_{12} \cdot x_{15}$ Euro/ton dry solid manure cake;
- Variable costs: $x_{12} \cdot x_{16}$ Euro/ton dry solid manure cake.

y_{28} = Pyrolysis costs only (pyrolysis step only) (Euro per ton dry solid manure cake). Pretreatment step is a drying step. The pretreatment costs are not included in the costs of the pyrolysis step

$$y_{28} = x_{12} \cdot (x_{15} + x_{16}) \text{ Euro/ton dry solid manure cake}$$

y_{29} = Total pyrolysis costs (Euro per ton wet solid manure cake). Pretreatment step is a drying step. These pretreatment costs are now included in the total costs of the pyrolysis process. Dry solid manure fraction of wet solid manure cake: $y_1/1000$ (-)

$$y_{29} = y_{25} + y_1 \cdot y_{28}/1000 \text{ Euro/ton wet solid manure cake}$$

y_{30} = Total pyrolysis costs (Euro per kg P_2O_5 present in the wet solid manure cake)

$$y_{30} = y_{29}/y_5 \text{ Euro/ kg } P_2O_5$$

No net energy production!

A2-4.3 Costs of incineration of wet solid manure cake without energy recovery

Investment of the incineration process without energy recovery: x13 Euro per ton (wet solid manure cake) annual treatment capacity installed.

Treatment costs (per ton wet solid manure cake):

- Capital costs: x13.x15 Euro/ton wet solid manure cake;
- Variable costs: x13.x16 Euro/ton wet solid manure cake.

It is assumed that the combustion value of the wet solid manure cake is more or less sufficient for an autotherm incineration process of the wet solid manure cake.

It is further assumed that there is no or only a negligible production of thermal or electrical energy

y31= Incineration costs (Euro) per ton wet solid manure cake

y31= x13.(x15 +x16) Euro/ton wet solid manure cake

y32= Incineration costs (Euro) per kg P₂O₅ present in the wet solid manure cake

y32= y31/y5 Euro/kg P₂O₅

No net energy production!

A2-4.4 Costs of incineration of wet solid manure cake with energy recovery

This process consists of two steps:

- The first process is drying of the wet solid manure cake. The energy necessary for the drying process is obtained from the incineration process of the dry solid manure cake. Because the incineration process directly follows the drying process it can be assumed that the water present in the wet solid manure cake is completely removed in the drying process. In the drying process the total amount of wet solid manure cake is strongly decreased. The amount of dry solid manure cake is substantially less than the amount of wet solid manure cake;
- The second step is incineration of the dry solid manure cake in combination with energy production (heat and electricity, or heat only).

Both processes are applied in the direct vicinity of each other. It is of course also possible to dry the wet sludge at another location than the incineration site. However in that case another destination for the waste heat that is produced in the incineration process (combined with electrical energy production) has to be found.

Investment of the drying process: x11 Euro per ton (wet solid manure cake) annual treatment capacity installed.

Treatment cost (per ton wet solid manure cake):

- Capital costs: x11.x15 Euro/ton wet solid manure cake;
- Variable costs: x11.x16 Euro/ton wet solid manure cake.

Investment of the incineration process with energy recovery: x14 Euro per ton (dry solid manure cake) annual treatment capacity installed.

Waste heat is used in the drying process.

Treatment costs (per ton dry solid manure cake):

- Capital costs: x14.x15 Euro/ton dry solid manure cake;
- Variable costs: x14.x16 Euro/ton dry solid manure cake.

y33= Incineration costs (Euro/ton dry solid manure cake) only (incineration + energy production) per ton dry solid manure. Pretreatment step is a drying step. The pretreatment costs are not included in the costs of the incineration step

$y33 = x14 \cdot (x15 + x16)$ Euro/ton dry solid manure cake

y34= Total incineration costs (Euro) per ton of wet solid manure. Pretreatment step is a drying step of the wet solid manure cake. The pretreatment costs are now included in the costs of the incineration step. Also the costs of energy production are included. The dry solid manure fraction of the wet solid manure cake amounts to y1/1000 (-)

$y34 = y25 + y1 \cdot y33 / 1000$ Euro/ton wet solid manure cake

y35= Incineration costs per kg P_2O_5 present in the wet solid manure cake (incineration with energy recovery)

$y35 = y34 / y5$ Euro/kg P_2O_5

A2-4.5 Calculations of the costs per ton slurry manure

Costs of Drying of wet solid manure cake per ton of wet solid manure CAKE (Euro/ton)

y25

Costs of Drying of wet solid manure cake per ton of SLURRY manure (Euro/ton)

$y25a = x1 \cdot y25$

Costs of Pyrolysis of wet solid manure cake per ton of wet solid manure CAKE (Euro/ton)

y29

Costs of Pyrolysis of wet solid manure cake per ton of SLURRY manure (Euro/ton)

$y29a = x1 \cdot y29$

Costs of Incineration (no energy recovery) of wet solid manure cake per ton of wet solid manure CAKE (Euro/ton)

y33

Costs of Incineration of wet solid manure cake per ton of SLURRY manure (Euro/ton)

$y33a = x1 \cdot y31$

Costs of Incineration + Energy recovery of wet solid manure cake per ton of wet solid manure CAKE (Euro/ton)

y34

Costs of Incineration + Energy recovery of wet solid manure cake per ton of SLURRY manure (Euro/ton)

$y34a = x1 \cdot y34$

A2-5 Calculation of energy demand and energy production

y36= Energy necessary for the drying process of 1 ton of wet solid manure cake (MJ/ton wet solid manure cake)

y36= y27 (MJ/ton wet solid manure cake)

y37= Energy content of 1 ton of dry solid manure cake (MJ/ton dry solid manure cake)

y37= 17000 (MJ/ton dry solid manure cake)

y38= Energy production from the incineration (with energy recovery) of the amount of solids present in one ton of wet solid manure cake (MJ/ton wet solid manure cake). Efficiency of the energy production (heat + electricity) is assumed to be 0.9

y38= (0.9).y1.x6 (MJ/ton wet solid manure cake)

y39= Production of electrical energy from the incineration (with energy recovery) of the amount of solids present in one ton of wet solid manure cake (MJ/ton wet solid manure cake). It is assumed that maximal 35% of the energy content (caloric value) of the wet solid manure cake can be converted in electrical energy

y39= (0.35).y1.x6 (MJ/ton wet solid manure cake)

y40= Production of heat per ton of wet solid manure cake (MJ/ton wet solid manure cake). This heat can be applied in the drying process of the wet solid manure cake

y40= y38-y39 (MJ/ton wet solid manure cake)

y41= Production of electricity per kg P_2O_5 present in the wet solid manure cake

y41= y39/y5 (MJ/kg P_2O_5)

y40a= production of electrical energy in the incineration (+energy recovery) process of wet solid manure cake per ton Slurry manure (MJ/ton)

y40a= x1.y39

The electrical energy required for the drying and incineration installation is not taken into account.

A2-6 Standard values of the relevant input parameter used in the excel calculation programme

x1=0.20(-)

x2=100 kg/ton slurry manure

x2a=0.7(-)

x3=25 kg/ton slurry manure

x3a=0.6(-)

x4=4 kgN-NH₃/ton slurry manure

xp=5 kg P_2O_5 /ton slurry manure

xpf=0.8(-)

x5=2.3 MJ/kg water

x6=17 MJ/kg solids

x7=0.9 (-)

x8=0.35 (-)

x9=0.4 (-)

$x_{10}=2 \text{ kg N-NH}_3$
 $x_{11}=100$
 $x_{12}=200$
 $x_{13}=200$
 $x_{14}=300$
 $x_{15}=0.1(-)$
 $x_{16}=0.15 (-)$

A2-7 Exploratory results and discussion

With the derived equations the effect of the various parameters on amount and composition of relevant products, treatment costs, energy demands and energy production can be calculated.
 In the calculations always the standard conditions are used as starting point. Only one parameter is varied.
 The other parameters are kept at the standard values.
 A few examples of such calculations are illustrated.

Table A1

Effect of ash concentration of the manure slurry manure (parameter x_3) on Ash content and P_2O_5 content.

Ash concentration of slurry manure (kg/ton) x_3	Ash content of dry solid manure cake (kg/ton) y_{11}	P_2O_5 content of dry solid manure cake (kg/ton) y_8	P_2O_5 content of the P-biochar (kg/ton) y_{19}	P_2O_5 content of the ash of incineration process (kg/ton) y_{21}
20.00	171	57	95	333
25.00	214	57	95	267
30.00	257	57	95	222

From Table A1 it is clear that the ash concentration of the manure slurry x_3 has a strong influence on the ash content of the wet solid manure cake. The P_2O_5 content of the P-biochar is not influenced, but the P_2O_5 content of the ash from the incineration process is strongly influenced by the value of x_3 . The P_2O_5 content of the ash is relatively high. It has to be noted that the assumption has been made that 80% of the amount of P_2O_5 present in the manure is concentrated in the wet solid manure cake.

Table A2

Effect of ash concentration of the slurry manure (parameter x3) on the amount of wet solid manure cake, dry solid manure cake, P-biochar and ash.

Ash concentration of slurry manure (kg/ton) x3	Amount of wet solid manure cake produced from 1 ton of manure slurry (kg/ton) y51	Amount of dry solid manure cake produced from 1 ton of manure slurry (kg/ton) y52	Amount of P-biochar produced from 1 ton of manure slurry (kg/ton) y53	Amount of ash produced from 1 ton of manure slurry (kg/ton) y54
20.00	200	70	42	12
25.00	200	70	42	15
30.00	200	70	42	18

From Table A2 it is clear that the ash amount x3 has only a strong influence on the amount of ash that is produced from 1 ton of manure slurry.

Table A3

Effect of solids content of the slurry manure (parameter x2) on the drying costs of the wet solid manure cake.

Solids content of the slurry manure (kg/ton) x2	Drying costs per ton wet solid manure cake (Euro/ton) y25	Drying costs of the wet solid manure cake per ton slurry manure (Euro/ton) y25a	Drying costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg) y26
80	25	5	1.25
100	25	5	1.25
120	25	5	1.25

Table A3 illustrates that the solids content x2 has no influence on the drying costs. It has to be noted that the energy necessary for the drying process has not been included in the drying costs. Incineration in combination with the production of electricity results in a sufficient amount of waste heat for drying the wet solid manure cake.

Table A4

Effect of investment for the drying installation (parameter x11) on the drying costs of the wet solid manure cake.

Investment for the drying installation per ton of wet solid manure cake installed treatment capacity (Euro/ton) x11	Drying costs per ton wet solid manure cake (Euro/ton) y25	Drying costs of the wet solid manure cake per ton slurry manure (Euro/ton) y25a	Drying costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg) y26
75	18.75	3.75	0.94
100	25	5	1.25
125	31.25	6.25	1.56

Table A4 shows that the drying costs are proportional to the investment for the drying installation. It has to be noted in that respect that the energy necessary for the drying process has not been included in the calculation of the drying costs.

Table A5

Effect of solids content of the manure slurry (parameter x2) on the total pyrolysis costs of the wet solid manure cake.

Solids content of the slurry manure (kg/ton) x2	Pyrolysis costs per ton wet solid manure cake (Euro/ton) y29	Pyrolysis costs of the wet solid manure cake per ton slurry manure (Euro/ton) y29a	Pyrolysis costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg) y30
80	39	7.8	1.95
100	42.5	8.5	2.13
120	46	9.2	2.3

Table A5 shows that the effect of the solids content of the manure slurry x2 on the pyrolysis costs is relatively low. This is caused by the fact that the drying costs of the wet solid manure cake are more or less independent of the solids content of the slurry manure and are a substantial part of the costs of the pyrolysis process. It has to be noted that the energy necessary for the drying process has not been included in the drying costs.

Table A6

Effect of solids content of the slurry manure (parameter x2) on the incineration costs of the wet solid manure cake.

System without energy recovery

Solids content of the slurry manure (kg/ton) x2	Incineration (without energy recovery) costs per ton wet solid manure cake (Euro/ton) y33	Incineration (without energy recovery) costs of the wet solid manure cake per ton slurry manure (Euro/ton) y33a	Incineration (without energy recovery) costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg P ₂ O ₅) y32
80	50	10	2.5
100	50	10	2.5
120	50	10	2.5

Table A6 illustrates that the solids content of the manure slurry x2 has no influence on the incineration costs. It is assumed that the water content of the wet solid manure cake has no influence on the incineration process (autothermic combustion).

Table A7

Effect of solids content of the manure slurry (parameter x2) on the incineration costs of the wet solid manure cake.

System with energy recovery

Solids content of the slurry manure (kg/ton) x2	Incineration (with energy recovery) costs per ton wet solid manure cake (Euro/ton) y34	Incineration (with energy recovery) costs of the wet solid manure cake per ton slurry manure (Euro/ton) y34a	Incineration (with energy recovery) costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg P ₂ O ₅) y35
80	46	9.2	2.3
100	51.25	10.25	2.56
120	56.5	11.3	2.83

Table A7 shows that the effect of the solids content of the manure slurry x2 on the incineration costs is relatively low. This is caused by the fact that the drying costs of the wet solid manure cake are independent of the solids content of the slurry manure and are a substantial part of the costs of the incineration process. It has to be noted that the energy necessary for the drying process has not been included in the drying costs. The incineration process provides sufficient waste heat for the drying process.

Table A8

Effect of the investment of the pyrolysis installation (parameter x12) on the total pyrolysis costs.

Investment for the pyrolysis installation per ton of dry solid manure cake installed treatment capacity, inclusive energy recovery for the drying of the wet manure cake (Euro/ton) x12	Pyrolysis costs per ton wet solid manure cake (Euro/ton) y29	Pyrolysis costs per ton slurry manure (Euro/ton) y29a	Pyrolysis costs per kg P ₂ O ₅ present in the wet solid manure cake (Euro/kg P ₂ O ₅) y30
200.00	42.50	8.5	2.13
300.00	51.25	10.25	2.56

Table A8 shows that the effect of the investment x12 on the pyrolysis costs is relatively low. This is caused by the fact that the drying costs of the wet solid manure cake are independent of the solids content of the slurry manure and are a substantial part of the costs of the pyrolysis process. It has to be noted that the energy necessary for the drying process and the pyrolysis process has not been included in the pyrolysis cost

Table A9

Effect of thermal energy required in the drying process of the wet solid manure cake (parameter x5) on the energy need and energy production in the incineration process with energy recovery.

Required net thermal energy for evaporation of 1 kg of water (MJ/kg) x5	Amount of energy necessary for the drying of 1 ton of wet solid manure cake (MJ/ton) y27	Heat production from the incineration (with energy recovery) of 1 ton of wet solid manure cake (MJ/ton) y40	Production of electrical energy from the incineration (with energy recovery) of wet solid manure cake, per kg P ₂ O ₅ present in the wet solid manure cake (MJ/kg P ₂ O ₅) y41
1.6	1040	3273	104
2.3	1495	3273	104
3.0	1950	3273	104

Table A9 shows that the effect of the thermal energy required in the drying process, x5, on the net energy production is relatively low. This is caused by the fact that the energy necessary for the drying process is in general only a moderate part of the total amount of energy that is produced in the incineration process.

Table A10

Effect of solids content of the slurry manure (parameter x2) on the energy need and energy production in the incineration process with energy recovery.

Solids content of the slurry manure (kg/ton x2)	Amount of energy necessary for the drying of 1 ton of wet solid manure cake (MJ/ton) y27	Heat production from the incineration (with energy recovery) of 1 ton of wet solid manure cake (MJ/ton) y40	Production of electrical energy from the incineration (with energy recovery) of 1 ton wet solid manure cake per ton slurry manure (MJ/ton slurry manure) y40a
80	1656	2618	333
100	1495	3273	417
120	1334	3927	500

Table A10 clearly shows that an increase in solids content of the manure slurry results in a strong increase in the net energy production.

A2-8 Conclusions

A2-8.1 Costs

From the Tables 1-10 it can be concluded that the costs of manure treatment per kg P_2O_5 present in the wet solid manure cake can be estimated as follows (costs in Euro/kg P_2O_5 present in the product, benefits from the products are not taken into account):

A. Drying wet manure cake	1-2
B. Production of P-biochar (including also the drying process)	2-4
C. Production of ash in an incineration process without net energy recovery (no drying process)	3-6
D. Production of ash from the incineration process with net energy recovery (including also the drying process)	3-5
E. Production of ash from the incineration process of the wet solid manure cake at SNB, using the surplus incineration capacity (no net energy production) (incineration costs per ton wet solid manure cake: 15 Euro per ton):	1.0
F. Transport of wet solid manure cake	1.0
G. Separation of slurry manure in wet solid manure cake and liquid fraction	0.5

The treatment costs of the liquid fraction obtained after mechanical separation of the manure and the benefits of the products from this liquid fraction have not been taken into account in the costs calculations.

The treatment costs of solid wet manure cake per kg P_2O_5 originally present in the wet solid manure cake can be translated to the costs per m^3 original slurry manure multiplying with a factor $x_p \cdot x_{pf}$ (from each m^3 manure $x_p \cdot x_{pf}$ kg P_2O_5 is concentrated in the wet solid manure cake).

A2-8.2 Potential benefits of P_2O_5 in ash

In the cost calculations the profits/revenues of the obtained products - energy, P_2O_5 containing ash, P-biochar - have not been taken into account.

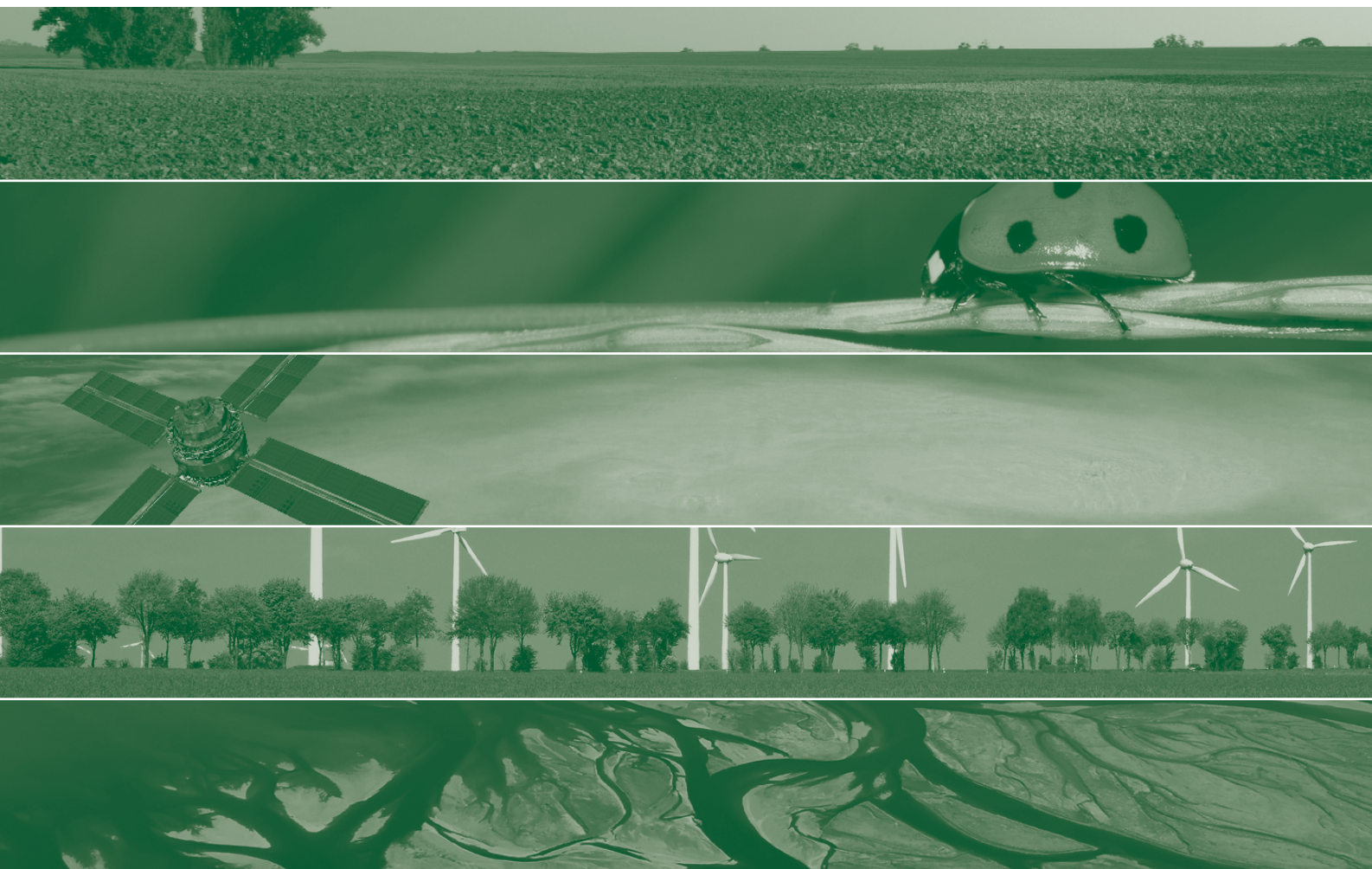
Costs of P-rock are currently about 50 Euro per ton P-rock. Costs can vary strongly. Looking to the future it can be expected that costs of P-rock will increase. Assuming minimum costs of 50 Euro/ton and maximum costs of 250 Euro per ton P-rock, and further assuming that the P-rock contains 250 kg P_2O_5 per ton than the costs of P_2O_5 as ore for P- and PO_4 production vary between 0.20 and 1 Euro/kg (present in the P-rock). Very briefly it can therefore be assumed that the benefits of the P_2O_5 in the ash of a manure incineration process have the same value.

A2-8.3 Potential benefits of the energy recovered

The potential amount of electrical energy that can be produced in the incineration process (with energy recovery) of wet solid manure cake amounts to about 100-150 kWh per ton slurry manure. The potential benefits of this amount of energy are substantially higher than the potential benefits of the amount of P_2O_5 that can be recovered per ton of slurry manure.

A2-8.4 Final conclusions

The final conclusion is that recovery of P_2O_5 from manure can economically only be feasible if the organic matter present in the manure is converted in electrical energy.



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