

DRAFT STRUBIAS Interim Report

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DRAFT market study for recovered phosphate salts, ash-based materials and pyrolysis materials in view of their possible inclusion as Component Material Categories in the Revised Fertiliser Regulation

Interim Report

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137 document are purely those of the authors and may not in any circumstances be regarded as
138 stating an official position of the European Commission. Neither the European Commission
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140 made of the information in this document.

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DRAFT - WORK IN PROGRESS

142 **1 STRUBIAS materials as CMCs in the Revised EU Fertiliser Regulation**

143 The Fertilisers Regulation revision aims at establishing a regulatory framework enabling
144 production of fertilisers from recycled bio-wastes and other secondary raw materials, in line
145 with the Bioeconomy strategy¹, which encompasses the production of renewable biological
146 resources and the conversion of these resources and waste streams into value added products.

147
148 In 2013, the European Commission organised a **Consultative Communication** that set out
149 for the first time at EU level the issues around the sustainability of phosphorus (P) use
150 (European Commission, 2013a). The intention was to launch a debate on the state of play and
151 the actions that should be considered. The European Institutions and all those interested –
152 organisations or private individuals – were invited to submit their comments on the questions
153 set out in the Consultative Communication, as well as on any other issues that they wish to
154 raise concerning the sustainable use of P. Phosphorus recycling has also been addressed by
155 FP7 research projects, the results of which have been analysed during the workshop 'Circular
156 approaches to phosphorus: from research to deployment', held in Berlin on 4 March 2015.

157
158 One of the identified priorities was to **revise the EU Fertiliser Regulation to extend its**
159 **scope to nutrients from secondary sources** (e.g. recycled phosphates) and organic sources.
160 At that moment, regulatory barriers to market rollout were noted, with the message that
161 coherent interpretation of existing relevant EU and national legislation is a precondition for
162 widespread implementation. Hence, a strong message from participants was **the need for**
163 **policy support for P recycling and for the nutrient circular economy**.

164
165 The presence of secondary raw materials in the initial list of CMCs is very limited. That is
166 due partially to the lack of agreed recovery rules and partially to the legal construction of the
167 Animal By-products Regulation (which the Commission therefore proposes to amend). For
168 that reason mainly, the Commission is empowered to extend the list of CMCs to additional
169 categories by Delegated acts. In recital 55 it has declared **its intention to do so for waste**
170 **and animal by-products "when the manufacturing processes have been scientifically**
171 **analysed and process requirements have been established at Union level"**.

172
173 Answers provided by European Institutions on the questions set out in the Consultative
174 Communication and workshop presentations indicated that promising technical progress is
175 being made in the field of recycling of waste. Amongst others, proposed actions included
176 removing of P from waste water in the form of **struvite, incinerating** and post-processing of
177 sewage sludge and fertilising product production from animal by-products in the form of
178 **biochar** through pyrolysis processes. This would boost domestic sourcing of plant nutrients
179 which are essential for a sustainable European agriculture, including P. It would also
180 contribute to a better implementation of the waste hierarchy, by minimising landfilling or
181 energy recovery of bio-wastes, and hence to solving related waste management problems.

182

¹ <http://ec.europa.eu/research/bioeconomy/index.cfm>

183 Based on this information, the European Commission decided to evaluate a possible legal
184 framework **for the production of safe and effective fertilisers from recovered, secondary**
185 **raw materials, such as biochar, ashes and struvite**. These could possibly be considered as
186 CMCs in the revised Fertiliser Regulation. The acronym STRUBIAS (STRUvite, Biochar, or
187 incineration Ashes)² was initially chosen as the working title for this project. Throughout the
188 course of the STRUBIAS project, the scope of these CMCs has, however, been further
189 refined as follows:

190

191 • Techno-scientific information obtained from the STRUBIAS sub-group³ indicated that
192 **struvite** that is precipitated with the intention of P-recovery is often a mixture of different
193 minerals. Moreover, P-recovery processes that rely on the principle of precipitation can
194 also intentionally target Ca- and Mg-phosphates other than struvite (e.g. dicalcium
195 phosphates). Therefore, the JRC STRUBIAS Interim Report on nutrient recovery rules
196 proposed to expand the scope of this CMC and to **change the name** of the CMC from
197 "struvite" to "**recovered phosphate salts**". This proposal received a large degree of
198 support from the STRUBIAS sub-group. Recovered phosphate salts involve substances
199 and mixtures dominantly composed of calcium and magnesium phosphates that have been
200 precipitated and isolated deliberately under controlled conditions and serve as an
201 ingredient for a plant nutrition product.

202

203 • The designation of **ash-based materials** was maintained and comprises both **raw ashes**
204 obtained from the incineration process as well as ashes that have been further **processed**
205 with the aim to partly remove heavy metals, increase the availability of plant nutrients in
206 the ash complexes or to form a complex multi-nutrient mineral fertiliser. Ash-based
207 materials involve substances or mixtures that contain materials that have undergone a
208 thermal oxidation process. Oxygen is not limiting the chemical reactions that transform
209 input materials into ashes and/or slags.

210

211 • The designation **pyrolysis material** is proposed for any material that is produced from
212 eligible input materials via production processes that cover the pyrolysis technology
213 spectrum including gasification and hydrothermal carbonisation techniques. Both
214 heterogeneous substances rich in aromatic carbon and minerals are considered. This
215 terminology offers the advantage that a clear reference is made to the production
216 technology in the name of the CMC. Pyrolysis materials involve substances or mixtures
217 that have undergone a pyrolysis, hydrothermal carbonisation or gasification process and

²Note that the acronym STRUBIAS was initially chosen as the working title for this project and has been maintained for simplicity reasons, despite a refined possible scope of the different groups agreed at the STRUBIAS Kick-off Meeting (Seville, July 2016)

³ The JRC is supported in the process by a technical working group, referred to as the STRUBIAS sub-group, that constitutes a sub-group of the Commission expert group on Fertilisers, which includes representatives from EU Member States, EU trade/business/professional associations, as well as from other institutions such as think tanks, research and academic institutions. The role of the subgroup is to participate in the process of sharing knowledge and providing non-binding expert advice to the European Commission on possible recovery rules for nutrients from eligible input materials into STRUBIAS materials.

218 serve as an ingredient for a plant nutrition product. The process takes place in an oxygen-
219 deficit environment or with a controlled amount of oxygen and/or steam that limit the
220 chemical reactions that transform input materials into chars or pyrogenic carbonaceous
221 materials.
222
223

DRAFT - WORK IN PROGRESS

224 **2 Objectives of the JRC STRUBIAS work**

225 The Joint Research Centre (JRC) of the European Commission is assessing the existing
226 techno-scientific evidence in view of a possible inclusion of materials containing STRUBIAS
227 as Component Material Categories (CMC) in the **Revised EC Fertiliser Regulation**⁴. This
228 assessment should form the basis for any technical proposals on the requirements that those
229 candidate materials shall comply with. After assessment, STRUBIAS materials could
230 possibly be used as **component materials** for the different Product Function Categories
231 (PFCs) included in the proposal for the Revised Fertiliser Regulation, more specifically
232 fertiliser, liming material, soil improver, growing medium, agronomic additive, plant
233 biostimulant, and fertilising product blend.

234
235 The JRC is supported in the process by a technical working group that constitutes a sub-
236 group of the Commission expert group on Fertilisers (hereafter **STRUBIAS sub-group**),
237 which includes representatives from EU Member States, EU trade/business/professional
238 associations, as well as from other institutions such as think tanks, research and academic
239 institutions. The role of the subgroup is to participate in the process of **sharing knowledge**
240 **and providing non-binding expert advice to the European Commission** on possible
241 recovery rules for nutrients from eligible input materials into STRUBIAS materials and
242 market aspects related to these materials.

243
244 The JRC **assesses STRUBIAS materials against following criteria** in order to provide
245 information on the appropriateness to include recovered phosphate salts, ash-based materials
246 and pyrolysis materials into Annex II of the Revised Fertilising Products Regulation by
247 delegated act:

- 248 I. *The material shall provide plants with nutrients or improve their nutrition*
249 *efficiency, either on its own or mixed with another material [following the*
250 *definition of fertilising products in the proposal for the Revised EC Fertiliser*
251 *Regulation];*
- 252 II. *The use of the materials will not lead to overall adverse environmental or*
253 *human health impacts;*
- 254 III. *Significant trade on the internal market can be expected for such a recovered*
255 *fertilising material, based on the current market and the future market and*
256 *trade forecasts.*

257
258 Should the European Commission conclude that it is appropriate to include recovered
259 phosphate salts, ash-based materials and pyrolysis materials into Annex II of the revised
260 Fertilising Products Regulation by delegated act, it would be worthwhile to assess the
261 possible impacts. This report therefore builds on the Interim Report on nutrient recovery rules
262 and supplements it by providing for a description of the impacts of the proposed recovery
263 rules elaborated under that work on:

⁴ More information on: http://europa.eu/rapid/press-release_IP-16-827_en.htm

264

265 (1) the foreseen EU market for fertilising products containing STRUBIAS materials and the
266 reasonable replacement potential of conventional fertilisers by such products;

267 (2) the environment and human health impacts of replacing conventional fertilisers by
268 fertilising products containing STRUBIAS materials resulting from the opening of the EU
269 market to such products; and

270 (3) the production and compliance costs of products complying with the proposed recovery
271 rules proposed and the impacts on the economy of replacing conventional fertilisers by
272 recovered fertilising products;

273

274 As the expected impacts obviously will depend on the precise formulation of proposed
275 nutrient recovery rules, the reports on nutrient recovery rules and the market study will be
276 strongly intertwined, and nutrient recovery rules may have to be established in an iterative
277 manner, taking into account the corresponding possible impacts. Therefore, it is important to
278 run this project concurrently with the work under nutrient recovery rules.

279

280 This Interim Report starts with a description of the **properties and the current fate of**
281 **eligible input materials** for STRUBIAS production processes (section 3), followed by an
282 overview of the **STRUBIAS production processes** (section 4). This contextual information
283 is required to make an informed choice for (1) the selection of relevant pathways for which
284 detailed process inventories and costs assessments (section 7.2) will be performed (to be
285 completed at a later stage in the STRUBIAS project), and (2) an assessment of processes that
286 are associated to a high technological readiness level to estimate the market for STRUBIAS
287 materials for the year 2030 (section 8.2).

288

289 **Agronomic efficiency** is a critical variable to determine the equivalence of P-fertilisers
290 derived from STRUBIAS fertilisers with mined and synthetic P-fertilisers. The market
291 outlook for STRUBIAS materials (section 8.2) is tightly linked to this parameter. Indirectly,
292 environmental and human health impacts are also related to this parameter that the fertiliser
293 application rates are interconnected to plant-available P, rather than to total P in the fertilising
294 material. The agronomic efficiency of STRUBIAS materials within a relevant European
295 context has been evaluated using meta-analyses techniques (section 5).

296

297 Possible adverse environmental or human health issues will be enforced by STRUBIAS
298 nutrient recovery rules, but **the impacts of the production and use phase** of STRUBIAS
299 materials will be evaluated in follow-up documents to this report.

300

301 **Economic aspects**, including estimates of production costs and sales prices, are presented in
302 section 7.

303

304 Finally, **an outlook of future market for STRUBIAS materials** has been given as well as
305 an estimation of the substitution effect of mined and synthetic fertilisers by fertilising
306 products containing recovered phosphate salts, ash-based materials and pyrolysis materials

307 for the year 2030 (section 8). Therefore, this document will cover aspects that relate to all
308 three criteria against which STRUBIAS materials will be assessed.
309

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310 **3 Potential input materials for fertilising products containing STRUBIAS materials**

311 **3.1 Introduction**

312 **Potential input materials** for the production of STRUBIAS materials include waste and by-
313 products within the meaning of Directive 2008/98/EC, animal by-products within the
314 meaning of Regulation (EC) No 1069/2009, and biological materials. Each of these input
315 materials have **specific properties**, including nutrient and contaminant contents, that impact
316 upon their suitability to be used as input materials for a specific STRUBIAS production
317 stream. This section aims at providing an overview of the characteristics for input materials
318 that have a high potential for nutrient recovery with a specific emphasis on P-recovery.

319
320 The works of van Dijk et al. (2016) and Buckwell and Nadeau (2016) provide an excellent
321 overview of the P-flows within the food and non-food production–consumption–waste chain
322 for the EU-27 (Figure 1). Although the work provides an overview for streams within the
323 year 2005, it provides a starting point for **designating material streams and core sectors**
324 **that are dominantly responsible for the dissipation of P into the environment**. In section
325 8, best estimates on the potential for P-recovery from the streams and sectors of interest for
326 the year 2030 through STRUBIAS will be provided.

327
328 It is indicated that the P-dissipation into the environment mainly takes place through losses
329 from crop production, food processing, and human consumption (Figure 1). Animal
330 production and non-food production are associated to lower losses (Figure 1) (van Dijk et al.,
331 2016).

332 Losses from **crop production** mainly occur due to P accumulation in soils (924 kt P yr⁻¹),
333 run-off and erosion (45 kt P yr⁻¹), and leaching and drainage to water bodies (40 kt P yr⁻¹).
334 Additional losses from the agricultural sector are observed due to diffuse losses from stables
335 (63 kt P yr⁻¹) (van Dijk et al., 2016).

336 Losses from **food processing** mainly originate from the slaughtering of animals and the
337 subsequent removal of P-rich rest materials (e.g. animal bones) from the biogeochemical P
338 cycles. This loss flow equals 294 kt P yr⁻¹ (van Dijk et al., 2016). Other loss streams for the
339 sector indicated by van Dijk et al. (2016) include food processing solid wastes (36 kt P yr⁻¹)
340 and wastewaters (9 kt P yr⁻¹).

341 Losses from **human consumption** are dominated by materials that are lost from waste water
342 treatment plants (van Dijk et al., 2016). About 227 kt P yr⁻¹ ends up in communal sewage
343 sludge, and an additional 74 kt P yr⁻¹ is lost as effluents from urban and decentralised waste
344 water treatment plants. Untreated and uncollected waste waters sum up a total of about 59 kt
345 P yr⁻¹. Other significant sources of P-dissipation from human consumption include food
346 waste from households, retail and food service (175 kt P yr⁻¹), pet excreta (69 kt P yr⁻¹) and
347 paper and wood waste (30 kt P yr⁻¹) (van Dijk et al., 2016).

348 The losses from **non-food production**, as designated by van Dijk et al. (2016), relate to
349 losses from forest-based industries (woodworking, furniture industry, pulp and paper
350 industry). The total losses equal 77 kt P yr⁻¹, with wood industry waste being the dominant
351 fraction (65 kt P yr⁻¹).

373

374 3.2 Crop residues

375 **Cereals** (283 Mt yr⁻¹ harvested wet material, averaged over the period 2005-2012, expressed
376 as wet matter) and **root crops** (173 Mt yr⁻¹ harvested, averaged over the same period) are the
377 most important types of crops in the EU-27, both **in terms of area cultivated (data not**
378 **shown) and production amounts** (Table 1) (Eurostat, 2016). Crop harvest of oil seeds (26
379 Mt yr⁻¹) and rice (3 Mt yr⁻¹) make up a smaller contribution to the overall total of 350 Mt yr⁻¹
380 for the EU (Table 1). Other crop types (e.g. other vegetables, nuts and non-food crops) were
381 not considered in this analysis as they make up a very small contribution to the EU overall
382 total crop production (Eurostat, 2016). Large differences exist between EU Member States,
383 due to the climate conditions, specific soil condition and farming practices (data not shown;
384 Eurostat, 2016).

385

386 The **residue-to-harvest ratio** varies widely across crop types, with the highest values
387 observed for oil seeds (1.5 – 2.1), followed by cereals (1.0 – 1.6) (Table 1) (Energy
388 Information Administration of the United States, 2001; Scarlat et al., 2010; Kremer, 2013).
389 Root crops generally produce minor amounts of residues relative to the harvested crop
390 biomass as the harvested tubers make up the dominant weight fraction of the plant biomass
391 (residue-harvest ratio varying from 0.2-0.4) (Table 1). **Root crops and oil seeds have**
392 **significantly higher N and P concentrations in their residues than cereals**, although large
393 differences in nutrient concentrations were observed among the different cereal crops (Table
394 1) (Kremer, 2013; Plants Database, 2016). Grain maize has, for instance, a nutrient content
395 that is about 3 to 4 times higher than wheat.

396

397 Regarding nutrient content, **cereals produce about half of the crop residue nutrients**
398 **present** (1353 kt N yr⁻¹, 279 kt P yr⁻¹), with the **other half split roughly equally between**
399 **root crops** (676 kt N yr⁻¹, 126 kt P yr⁻¹) and **oil seeds** (743 kt N yr⁻¹, 150 kt P yr⁻¹). Five crop
400 types (wheat and spelt, grain maize and corn-cob mixtures, sugar beet, sunflower seeds and
401 rape and turnip rape seeds), contribute for 71%-73% of the nutrients generated as crop
402 residues (Table 1).

403

404

405 **Table 1: Production, characteristics and nutrient contents of agricultural crop residues in the**
 406 **EU-27, averaged for the period 2005-2012 (Sources: Energy Information Administration of the**
 407 **United States (2001); Eurostat (2016); Kremer (2013); Plants Database (2016); Scarlat et al.**
 408 **(2010))**

crop	harvest (Mt yr-1)	residue-to- harvest ratio (-)	residue dry matter content (Mt yr-1) ¹	residue nutrient concentration		residue nutrient content	
				N (%)	P (%)	N (kt yr-1)	P (kt yr-1)
cereal	283		292			1353	279
wheat and spelt	136	1.3	150	0.28	0.05	419	73
barley	57	1.2	58	0.43	0.09	248	50
grain maize and corn-cob-mix	61	1.0	47	0.81	0.20	384	96
oats and spring cereal mixtures	12	1.3	14	0.70	0.14	101	20
rye and winter cereal mixtures	8	1.6	12	0.48	0.11	57	13
triticale	10	1.3	11	1.30	0.24	144	27
rice	3	1.4	3	0.67	0.13	23	5
root crops	173		40			676	126
potatoes	59	0.4	20	1.10	0.18	224	36
sugar beet	115	0.2	20	2.28	0.45	452	89
oil seeds	26		38			743	150
sunflower seeds	7	2.1	12	2.84	0.58	351	71
rape and turnip rape seeds	19	1.5	26	1.53	0.31	392	78
overall total	350		374			2795	559

¹calculated based on residue-to-harvest ratio and residue dry matter content

409
 410
 411 A distinction, however, has to be made between residues remaining in the field and those
 412 generated after harvesting. The majority of the crop residue is not collected and removed, but
 413 **ploughed back into soil as its collection is too expensive to be profitable.** Additionally,
 414 agricultural residues play an important role in **maintaining or improving soil**
 415 **characteristics**, protecting the soil from erosion, maintaining or increasing soil organic
 416 matter, maintaining nutrients in the soil and improving water retention (Nelson, 2002 in
 417 Scarlat, 2010). Therefore, it is recommended to leave a significant share of the crop residues
 418 on the field for agricultural sustainability, dependent on crop type, farming practices, site
 419 conditions, and climate. The current best practice of incorporation for the EU is of one-third
 420 of total residues (Joint Research Centre, 2009), although other studies have reported even
 421 higher values of 40%-50% (Scarlat et al., 2010).

422
 423 **Crop residues are only collected if there is an economic potential, for instance, for their**
 424 **use as animal feed, bedding material or biofuel.** The economic viability increases if
 425 fertilising materials from crop residues are produced as part of a cascading approach that
 426 relies on the residues of the primary process of recovery of valuable organic substances from
 427 crop residues (e.g. lactic acid, citric acid, ethanol, caffeine, yeast production, biogas
 428 production, etc.).

429 At present, harvested residues are used for many often **onsite-specific purposes**: food,
 430 fodder, feedstock, fibre, and further use such as compost production. Some amount of crop
 431 residues is also collected for mushroom cultivation and various horticultural uses. Scarlat et
 432 al. (2010) estimated that about 26 Mt yr⁻¹ of residues are used in animal husbandry and

433 another 1.6 Mt yr⁻¹ of residue for mushroom production over the whole of the EU. The uptake
434 of crop residues by the animal husbandry sector largely depends on the farm ratio of livestock
435 to crop, for which higher values were documented for countries with high relative livestock
436 proportions (e.g. for the UK, Searle and Malins, 2013). Much of the residue consumption for
437 livestock occurs on site, i.e., the same farmer who harvests cereals and collects the straw
438 feeds it to his or her livestock. Wheat and barley straw are also traded in Europe for use in the
439 livestock sector. Some residues are sold to other parties, and this amount is easier to track.
440 Studies have estimated off-farm residue use to amount to 5% - 6% (Kim and Dale, 2004).

441
442 Crop residues are often cited and explored for **their energy recovery potential**, but at
443 present, crop residues are only used to a very small extent throughout the EU. Available EU-
444 level data indicate that dedicated energy cropping for biofuels and electricity and heat
445 generation covered approximately 5.5 million hectares of agricultural land in 2008
446 (ETC/SIA, 2013), or about 3% of the EU utilised agricultural area. Practically all of this land
447 was used for dedicated biofuel cropping (bioethanol and biodiesel). The realistic potential
448 derived from the technical-sustainable potential for agricultural crop residues to contribute to
449 renewable energy production has been estimated at 75 million tonnes per year in the EU-28,
450 with a dominant contribution of the cereals wheat (26%), maize (21%) and barley (16%)
451 (Iqbal et al., 2016). Based on the P content as given in Table 1, **the total P content in the**
452 **crop residues that could be used in nutrient recovery processes is estimated at around**
453 **110 kt P yr⁻¹**. Nutrient recovery from crop residues used for renewable energy production
454 could potentially be a value-adding life stage or end-of-life solution for materials subject to
455 anaerobic digestion for biogas production, or other thermochemical energy recovery
456 processes. Such pathways are compatible with the production of **recovered phosphate salts**
457 (after anaerobic digestion, although concerns exist due to the low phosphate content of
458 anaerobically digested crop residues), **ash-based materials** (Insam and Knapp, 2011), and
459 **pyrolysis materials** (EBC, 2012).

460

461

462 **3.3 Manure**

463 The **EU farm livestock population** consists of 153 million pigs, 88 million cattle, 1.3 billion
464 poultry, 83 million sheep and 10 million goats (FAOSTAT-Commodity Balances Livestock,
465 2012). Together, the **livestock excretes around 1400 Mt of manure** (Table 2) (Gendebien et
466 al., 2001; Foget et al., 2011; Agrotechnology Atlas, 2016; Buckwell and Nadeu, 2016). Cattle
467 manure (1092 Mt) represents the dominant manure fraction, with amounts that are about one
468 order of magnitude greater than for pig (177 Mt) and poultry (112 Mt) (Foget et al., 2011)
469 (Table 2). The manure produced from other livestock groups is mostly deposited directly on
470 land by grazing animals. Production and characteristics of manure on a farm are largely
471 **affected by species and growth stages of animals, feed ratios, manure collection and**
472 **handling methods, and the amount of water added into the manure collection systems**
473 (Agrotechnology Atlas, 2016).

474

475 Animal manure contains complex organic compounds originated from the undigested and
476 wasted feed and veterinary products as well as simple organic and inorganic compounds
477 produced in the gastrointestinal tract of animals. Hence, **manure slurry** is a mix of faeces
478 and urine from livestock, bedding material with small structure like sawdust or chopped
479 straw, washing water, water spill, etc. and originating from stables with whole or partly
480 slotted floors (Bicudo, 2009). **Solid-liquid separation**, possibly after anaerobic digestion, is
481 often used as a treatment method from improving manure handling properties and producing
482 manure solids for energy generation, compost production and animal feeding. Another goal
483 for solid liquid separation is to produce fertiliser products with different ratios of nitrogen to
484 P and N to potassium (K) serving a better tuning with crops requirements for nutrients.
485 Manure is removed from the livestock stables on a frequent (for instance daily) basis, and
486 placed in a manure pad with drains, enabling to collect liquid fractions such as urine, silage
487 effluents, process water and alike, in separate stores, and vice versa with the solid fractions.
488 A broad variety of solid-liquid separation techniques is, however, available (Hjorth et al.,
489 2010). Effective solid-liquid separation that is capable of removing a substantial amount of
490 organic solids from fresh liquid or slurries can potentially offer the benefits of production of
491 nutrient-rich organic solids, odour reduction in the subsequent liquid manure storages, and
492 improvement in the economics of **subsequent liquid manure treatment processes**. The
493 separated **manure solids** can be utilized on farms near animal operations or can be
494 economically exported to other areas as fertiliser and soil conditioning products
495 (Agrotechnology Atlas, 2016). Alternatively, livestock is kept in stables where on a bed of
496 long straw or similar material, up to 1 metre thick. The bed, also referred to as **deep litter**, is
497 only removed with intervals of up to one year, when the livestock is removed from the stable
498 for slaughter or grazing (Agrotechnology Atlas, 2016).

499
500 In spite of the vast nutrient amounts present in manure, these are present in highly diluted
501 form as manure has an **average dry matter content of only 19%** (Table 2). The dry matter
502 content is lowest for pig manure, with values as low as 5% for the largest share of the pig
503 manure (pig slurry, Table 2). The **nutrient content of manure stocks varies broadly with**
504 **the origin of the manure (cattle, pig, and poultry) and the type and extent of separation**
505 (Table 2). Across the different origins of manure, poultry and pig slurries have the highest N
506 and P concentrations with values of 5.8% - 8.3% and 2.2% - 2.3%, for N and P, respectively
507 (Table 2). The N/P ratios of most manure types vary between 2 and 5, with the exception of
508 liquid cattle manure that has an N/P ratio of about 12 (Table 2). All manure types have
509 generally high organic matter contents (range 57% - 82%) (Table 2).

510
511 Cattle is the dominant manure fraction when data are expressed on a nutrient content basis.
512 **Cattle manure contributes for 61% and 54% of the N and P present in the total**
513 **livestock manure**, respectively (Table 2). **Poultry** manure is another significant nutrient
514 stream, especially for P (36% of the total manure, up to 883 kt P yr⁻¹) and to a slightly lesser
515 extent for N (30% of the total manure) (Table 2). **Pig** manure contributes for 9% (for N) and
516 10% (for P) to the total nutrients presents in manure (Table 2). Poultry and pig are often kept
517 inside year-round, for which reasons their manure can be easily collected.

518 **Table 2: Amount of manure in the EU-27 and its composition (sources: Agrotechnology Atlas (2016); Foget et al. (2011); Gendebien et al. (2001))**

	Amount	Dry matter	Organic matter	N/P	K			N			P		
					concentration	content	relative contribution	concentration	content	relative contribution	concentration	content	relative contribution
	(Mt yr ⁻¹)	(%)	(% of dry matter)	(-)	(% of DM)	(kt K yr ⁻¹)	(%)	(% of DM)	(kt N yr ⁻¹)	(%)	(% of DM)	(kt P yr ⁻¹)	(%)
Pig slurry	148.6	5	69	3.7	4.6	373	4.7	8.3	673	7.2	2.2	181	7.3
Source separated pig manure							0.0			0.0			0.0
Solid	14.2	24	80	2.4	2.0	71	0.9	3.2	113	1.2	1.4	48	1.9
Liquid	8.8	2	n.a.	5.4	9.1	14	0.2	17.1	27	0.3	3.2	5	0.2
Pig deep litter	5.3	28	75	2.5	4.0	59	0.7	2.3	35	0.4	0.9	14	0.6
Total pig	176.9	7				517	6.5		847	9.1		248	10.0
Cattle slurry	447.8	9	66	4.6	4.7	1899	23.9	4.5	1818	19.6	1.0	399	16.1
Source separated cattle manure													
Solid	294.9	22	64	3.3	2.1	1371	17.2	2.4	1557	16.8	0.7	475	19.2
Liquid	54.6	3	57	12.5	29.4	447	5.6	12.2	185	2.0	1.0	15	0.6
Cattle deep litter	294.9	25	77	4.7	3.2	2397	30.2	2.9	2135	23.0	0.6	454	18.4
Total cattle	1092.1	17				6114	76.9		5694	61.3		1342	54.3
Poultry slurry	3.4	14	82	3.0	2.6	13	0.2	6.8	33	0.4	2.3	11	0.5
Poultry deep litter	109.5	57	74	3.1	2.1	1307	16.4	4.4	2713	29.2	1.4	872	35.3
Total poultry	112.9	55				1319	16.6		2746	29.6		883	35.7
Overall total	1381.9	19	69	4.4		7950			9287			2473	

519

520 It should be noted that the numbers for P presented in Table 2 differ from the ones presented
521 in van Dijk et al. (2016). In their study, a total manure flux of 1.75 Mt P yr⁻¹ was observed for
522 the reference year 2005, in contrast to the number of 2.47 Mt P yr⁻¹ as presented in Table 2.
523 The reasons for this discrepancy relate to the different reference years that are used in the
524 studies, and the uncertainty in average values for the nutrient concentrations and dry matter
525 contents of the diverse manure fractions. Hence, estimating manure nutrient inputs is
526 associated to a significant degree of uncertainty, and the absolute numbers given should be
527 interpreted with the necessary caution.

528
529 **The main fate of manure in the EU-28 is currently land application.** At present, more
530 than 90% of the manure produced in the EU is returned to agricultural land either through the
531 spreading of the collected manure or directly by outside grazing activities (Buckwell and
532 Nadeu, 2016). Only 7.8% of the produced manure, or 139 kt P, was processed in the year
533 2010 (Foget et al., 2011).

534
535 **Landspreading of manure involves a risk for the accumulation of potentially toxic**
536 **elements, pathogen recycling, and odour nuisance** (Gendebien et al., 2001). Manure may
537 contain significant amounts of metals/metalloids due to the use of mineral supplements and
538 veterinary products. This is particularly true for pig slurry, which can contain up to 600 mg
539 kg⁻¹ dry matter of Cu, and up to 900 mg kg⁻¹ dry matter of Zn. Also, cattle slurries contain
540 high amounts of Zn (up to 750 mg kg⁻¹ dry matter) (Gendebien et al., 2001). Considering the
541 large volumes of manure applied, metals/metalloids may accumulate as a result of long-term
542 agricultural use. Accumulation of metals/metalloids could not only affect the soil fertility, but
543 also promote metal migration through leaching and runoff. Additionally, there is also
544 growing concern regarding the environmental fate and potential impacts of the veterinary
545 pharmaceuticals on human and ecosystem health as animal feeding pharmaceuticals are
546 excreted into manure either as parent compounds or as bioactive metabolites (Song et al.,
547 2010). Finally, animal manures contain pathogenic elements in variable quantities depending
548 on the animal health. Manures applied without treatment and restriction on the application to
549 land represent a risk for possible re-infection of resident animal population and the
550 contamination of meat, dairy products, vegetables and water resources. There have been
551 reports on cases of drinking water supplies contaminated by cattle slurry resulting in
552 outbreaks of human diseases (Gendebien et al., 2001; Spellman and Whiting, 2007). The
553 sources of ammonia emissions and odour nuisance from livestock production are from animal
554 housing, waste handling, storage and landspreading. The storage of pig and poultry manure
555 may cause odour problems if wastes turn anaerobic and give rise to strong odour when the
556 crust is broken.

557
558 While nutrient recovery has **an enormous, positive role in well-adjusted agricultural**
559 **systems**, much of the recycled manure is often **applied according to non-sustainable**
560 **practices** due to spatial constraints associated to high transport costs of the large-volume
561 material and unbalanced nutrient supply stoichiometry. This may lead to P accumulation in
562 soil and water eutrophication after the leaching of nutrients from the soil.

563

564 In the legal sense, the animal by-products regulation (EC/1069/2009) classifies manure as an
565 animal by-product of category 2. According to this regulation, **manure can be applied on**
566 **land without further processing**. Possible manure **use restrictions** are, however, defined in
567 other EU legislation.

568
569 The **Water Framework Directive** (WFD, 2000/60/EC) establishes an integrated and co-
570 ordinated framework for the sustainable management of water, including prevention of
571 deterioration of water bodies (lakes, rivers, coastal and transitional, groundwater), promotion
572 of sustainable water use, and ensuring “enhanced protection and improvement of the aquatic
573 environment”. The **Nitrates Directives** (91/676/EEC) indirectly limits the return of P to land
574 by limiting the amount of N in manure that can be applied on land. However, the
575 stoichiometric N/P ratios documented for soil microbes and plants (around 6 - 8; Cleveland
576 and Liptzin, 2007) are higher than the N/P ratios of most types of manure (on average 4.4,
577 Table 2). This indicates that **even manure applied to land in line with the Nitrates**
578 **Directive contributes significantly to the observed P accumulations** in agricultural
579 ecosystems that receive high manure loads (Figure 1; van Dijk et al., 2016). Member states
580 (Belgium (Flanders, Wallonia), Denmark, the Netherlands, UK, Northern Ireland, Ireland)
581 who have or had (Germany, Austria) an derogation for the use of N from animal manures
582 (Nitrates framework directive) have to meet requirements of sound fertilisation practices
583 which already leads to a more balanced nutrient management. In the Netherlands, for
584 instance, manure processing is obligatory in case a farm has insufficient land to apply animal
585 manure according the regulatory application standard. It is estimated that in 2015 about 8.9
586 kT P yr⁻¹ from animal manure was processed in the Netherlands (MBA, 2015), with an
587 additional 4.9 kT P yr⁻¹ being planned. **Integrated pollution control**, as a principle of
588 environmental protection and management, aims to minimize the overall environmental
589 impact of human activities by taking into account pollution of air, water, land and the human
590 environment, and identifying the action that causes on balance the least damage. As a legal
591 system, integrated pollution control has been adopted by the European Union and, with an
592 extended remit, been put in force as integrated pollution prevention and control (IPPC). IPPC
593 covers intensive animal rearing for farms with a capacity of greater than 40,000 animal places
594 for poultry, 2000 for fattening pigs and 750 for sows. New farms and those with extensive
595 modifications have to comply immediately whereas existing farms had to do so by 2007.
596 Following inter-institutional negotiations, the Directive on industrial emissions 2010/75/EU
597 (IED) was adopted on 24 November 2010. The IED repeals the IPPC Directive and the
598 sectoral directives as of 7 January 2014. The IED requires ‘**best available techniques**’ to be
599 applied in the operation of an installation. This will include measures for the management of
600 manure/slurry within the installation (e.g. its removal from animal houses) and methods for
601 its storage so as to prevent or minimise environmental impacts.

602
603 Eurostat monitors the risk of P pollution from agriculture based on the indicator "**gross P**
604 **balance**", indicative for the potential surplus of P. The P balance lists all inputs and outputs
605 into and out of the soil and calculates the gross P surplus as the difference between total
606 inputs and total outputs. The gross P surplus per ha is derived by dividing the total gross
607 phosphorus surplus by the reference area.

608 The inputs of the phosphorus balance are:

- 609 • Fertilisers, which consist of:
 - 610 • inorganic fertilisers;
 - 611 • organic fertilisers (excluding manure).
 - 612 • Gross manure input, which is calculated from:
 - 613 • manure production (phosphorus excretion);
 - 614 • manure withdrawals (manure export, manure processed as industrial waste,
 - 615 non-agricultural use of manure, other withdrawals);
 - 616 • change in manure stocks;
 - 617 • manure import.
 - 618 • Other phosphorus inputs, which consist of:
 - 619 • seeds and planting material;
 - 620 • atmospheric deposition.
- 621

622 The outputs of the gross phosphorus balance are:

- 623 • Total removal of P with the harvest of crops (cereals, dried pulses, root crops,
 - 624 industrial crops, vegetables, fruit, ornamental plants, other harvested crops).
 - 625 • Total removal of P with the harvest and grazing of fodder (fodder from arable land,
 - 626 permanent and temporary pasture consumption).
 - 627 • Crop residuals removed from the field.
- 628

629 The indicator provides an indication of the potential surplus P on agricultural land (kg P per
630 ha per year). The quality and accuracy of the estimated gross P surplus per ha depends on the
631 quality and accuracy of underlying data and coefficients used. As methodologies (especially
632 with regards to the coefficients) and data sources used in countries vary, the balances are only
633 consistent within a country across time. The gross P balances are not consistent across
634 countries implying that data cannot be compared between countries. It should be noted that
635 data on **manure withdrawals, manure stocks and imports** were not **available in most**
636 **countries**. Available data on manure withdrawals for non-agricultural use show that this
637 input is significant (more than 5% of total manure input) in some countries (Belgium, the
638 Czech Republic, the Netherlands), while non-significant in other countries (the United
639 Kingdom, Switzerland).

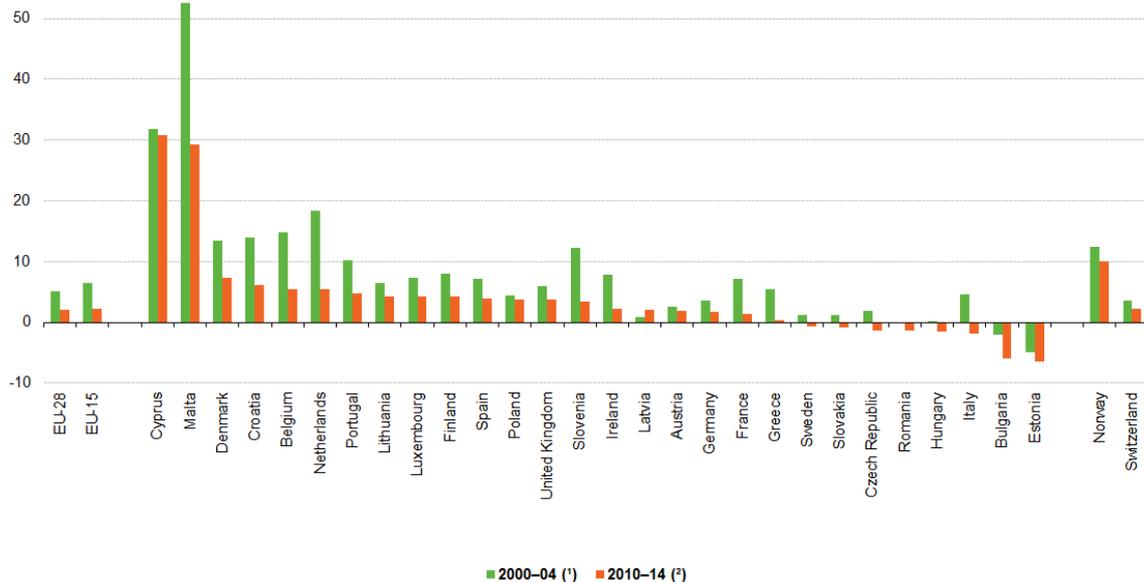
640

641 The gross P balance can only indicate the **potential risk** to the environment while the **actual**
642 **risk for water eutrophication depends on many factors including climate conditions, soil**
643 **type and soil characteristics, management practices such as drainage, tillage, irrigation,**
644 etc. The risk of P pollution is only partially determined by the P balance of a particular year.
645 It is often more strongly determined by the cumulative P balance of the past.

646

647 The **potential P surplus for the EU-28 decreased from an estimated average of 5.2 kg P**
648 **per ha per year in the period 2000-2004 to 1.9 kg P per ha per year in the period 2010-**
649 **2014**. For the EU-15 the potential P surplus dropped from on average 6.4 kg P per ha per year
650 in 2000-2004 to an average of 2.3 kg P per ha per year in 2010-2014. The average potential P

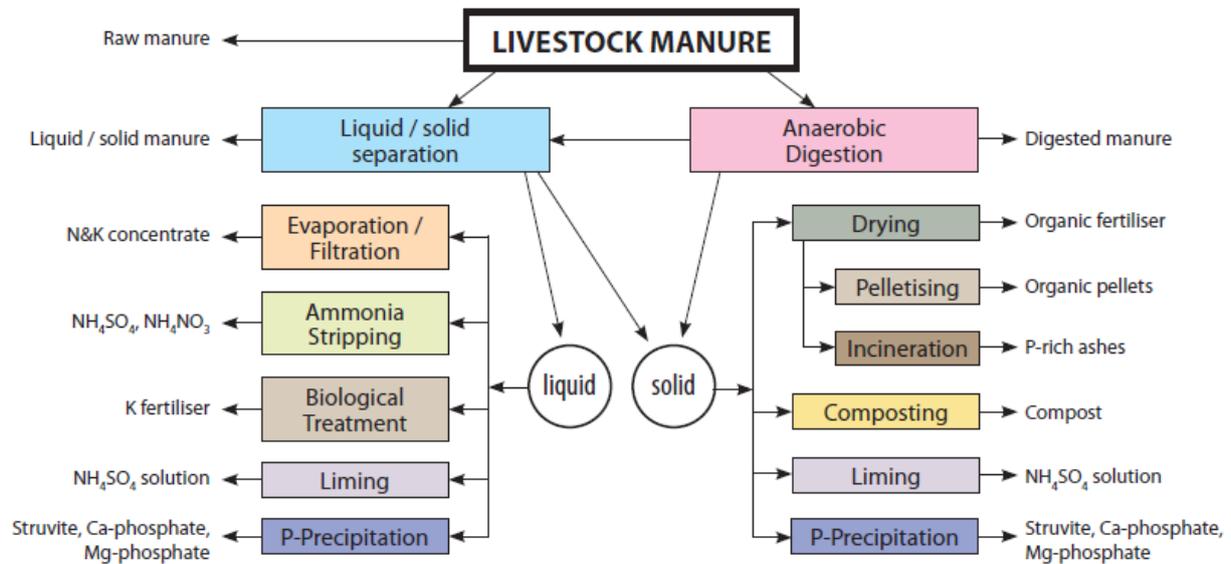
651 surplus per ha in 2010-2014 was highest in the Mediterranean islands Cyprus and Malta,
 652 above the EU average in Norway, Denmark, Croatia, Belgium, the Netherlands, Portugal,
 653 Lithuania, Luxembourg, Finland, Spain, Poland, the United Kingdom, Slovenia, Switzerland,
 654 Ireland and Latvia while the balance was negative for Sweden, Slovakia, the Czech Republic,
 655 Romania, Hungary, Italy, Bulgaria and Estonia (Figure 2). In all Member States, with the
 656 exception of Latvia, the potential P surplus between 2010 and 2014 was lower than between
 657 2000 and 2004.



Note: Eurostat estimates for EU-28, EU-15, Belgium, Bulgaria, Denmark, Greece, Spain, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Austria, Romania and Slovakia.
 (*) Estonia: 2004
 (*) Germany, Ireland, Sweden and Switzerland: 2010-13

658
 659 **Figure 2: Gross phosphorus balance, averages 2000–04 and 2010–14 (Source: Eurostat - Agri-**
 660 **environmental indicator - risk of pollution by phosphorus)**
 661

662 Nonetheless, **there is still a clear scope to increase the efficiency of nutrient recycling in**
 663 **the agricultural sector. One option is through manure treatment options** that aim at
 664 producing a safer, lower volume, and more targeted fertiliser that better matches crop needs.
 665 At current, **7.8% of the manure (108 Mt, 556 kt N, 139 kt P) is being collected for**
 666 **treatment** in the EU (Foget et al., 2011; Flotats et al., 2013). Distributed on livestock manure
 667 treatments, pig slurry is a major focal area for treatment due to the high transport costs for the
 668 highly diluted manure and the small surface area to dispose the slurry produced (Foget et al.,
 669 2011). Two major routes are applied individually or combined to process manure with the
 670 objective to change the physical and chemical manure properties, to recover energy or to
 671 prepare for nutrient removal from the stream (Foget et al., 2011) (Figure 3).
 672



673

674

Figure 3: Overview of the possible routes for nutrient recovery for livestock manure (adopted from Buckwell and Nadeu, 2016)

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Separation via mechanical, chemical or other technologies is applied to treat 49 Mt of livestock manure, while anaerobic digestion is applied for 88 Mt of material (Buckwell and Nadeu, 2016). In almost all types of separation, organic and inorganic coagulants and flocculants are applied to achieve a good separation between the solid and liquid phase, resulting in the precipitation of suspended solids and the concentration of the phosphates in the solid fraction. The use of coagulants and flocculants results in an increase of the costs of the mechanical separation process, and some flocculants (polyacrylamide) have adverse environmental effect. Their use also has a strong effect on the further treatment potential of the solid and liquid fraction (Schoumans et al., 2010), although new technologies are emerging. Usual coagulants and flocculants are polyelectrolytes, aluminum and iron sulphate, aluminum and iron chloride, calcium oxides and calcium hydroxides, and also magnesium oxide and magnesium hydroxides. In case of targeting P-recovery in agriculture, the use of metal-containing salts might potentially impact upon the adeptness for P-recycling.

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Recovery of biogas during **anaerobic digestion** is advantageous as it can be used for electric energy generation or for the heating and drying during the further processing of manure. Additionally, anaerobic digestion increases the dewatering properties of the slurry as more components end up in the solid fraction following separation of the slurry, and the drying of the solid fraction proceeds more rapidly (Schoumans et al., 2010). The solid fraction can then be dried before pelletising or following incineration, or alternatively, composting is used. For 0.7% of the manure production in the EU, the liquid fraction is further processed, mostly through biological treatment via conventional nitrification – denitrification systems and concentration through evaporation or filtration methods to produce a mineral concentrate (Foget et al., 2011; Buckwell and Nadeu, 2016). In the Netherlands, reverse osmosis techniques are used to produce NK fertilisers from liquid fractions of separation of animal manure or digestates. Substantial variations in the extent of manure processing and the different manure processing techniques are observed across EU member states (Foget et al.,

2011). The other options displayed in Figure 3 are technically viable, but do not make a substantial contribution at the time present.

705

Manure and stable livestock slurries are used as inputs for operational STRUBIAS processes. Stichting Mestverwerking Gelderland produces **K-struvite** from veal manure in the Netherlands. Also the EU funded BioEcoSim project aims at producing a mixture of recovered phosphate salts (from pig manure). Different companies in the Netherlands and the UK (e.g. BMC Moerdijk, Fibrophos, etc.) produce **poultry litter ashes** from a combination of slaughtered animals and poultry beds. Finally, Hitachi-Zosen and the BioEcoSim project are evaluating the possibility of establishing a **poultry manure pyrolysis facility** in central Europe based on experience obtained from their pilot plant in Japan.

714

715

716 **3.4 Animal by-products other than manure**

717 3.4.1 Food waste from households, retail and food services

Food waste in the household sector involves **waste associated to meal preparation, leftovers, and purchased food not used in time**. Causes for this waste are diverse and relate to a lack of awareness and cooking skills, personal preferences, improper planning, labelling issues, storage and inappropriate portion sizes. In **wholesale/retail**, waste accumulates as a result of damage and expiry of products or surplus due to supply chain inefficiencies, improper stock management and deficient storage. Finally, additional aspects that cause waste from the **food services** include the single portion size, overstocking and meeting specific customer wishes (e.g. school children, etc.) (Bio Intelligence Service - Umweltbundesamt - AEA, 2010). Legally, waste from households, retail and food service waste containing products of animal origin is **category 3 animal by-product material**.

728

The amount of food waste generated from households, retail and food services is estimated at **62 Mt fresh material yr⁻¹, of which about three quarters (73%) is household waste, 17% is food services and 8% is retail** (Stenmark et al., 2016). The **nutrient content** of food waste is largely dependent on the exact composition (fraction animal and plant origin), but generally ranges from **1.6% - 2.3% for N and 0.26 - 0.54% P**. The dry matter content varies in the range 15% - 29% of the fresh weight (Brink, 1993; Widen, 1993). Hence, it is estimated that food waste from households, retail and food service could contain around **25-100 kt P per year**.

737

The current fate of the separately collected food waste is highly Member State specific. Currently, there is **no direct obligation at the EU level to recycle biodegradable waste** resulting in great differences across Member States. The Landfill Directive (1999/31/EC) obliges Member States, however, to reduce the amount of biodegradable municipal waste that they landfill to 35% of 1995 levels by 2016 (for some countries by 2020). On 2 July 2014, the European Commission adopted a legislative proposal to review waste-related targets in the Landfill Directive as well as recycling and other waste-related targets in Directive 2008/98/EC on waste and Directive 94/62/EC on Packaging and Packaging Waste. The

746 proposal aims at phasing out landfilling by 2025 for recyclable waste (including plastics,
747 paper, metals, glass and bio-waste) in non-hazardous waste landfills, corresponding to a
748 maximum landfilling rate of 25%.

749

750 Biodegradable waste **is a suitable input material for nutrient recycling options, such as**
751 **composting and anaerobic digestion**, thanks to the low heavy metal content and high bio-
752 availability of the nutrients. A critical aspect is, however, to what extent the separate
753 collection and processing of food waste can be achieved.

754

755 In the **legal sense**, food waste is treated in the same way as normal waste that is non-
756 hazardous if and only if it does not exhibit any properties that may render it hazardous.
757 **Products of animal origin, or foodstuffs containing products of animal origin, and**
758 **catering waste are, however, classified as category 3 Animal By-products**. Stringent
759 controls are applied to its transport, handling and storage, treatment and disposal through
760 Animal By-Products Regulation (EC) No 1069/2009. **Therefore, a share of the food waste**
761 **is processed together with slaughter residues by the rendering industry** (see paragraph
762 3.4.4).

763

764 3.4.2 Materials from the fish industry

765 In 2012 the fish processing sector in the EU comprised approximately 3,500 firms with fish
766 processing as their main activity (Doring and Borrello, 2014). Italy possessed the largest fish
767 processing industry in 2012 in terms of number of firms (16% of the total) and the United
768 Kingdom in terms of people employed (16% of the total), followed by Spain and France
769 (Doring and Borrello, 2014). This sector includes activities such as the processing of white or
770 pelagic fish; fatty fish; shellfish, i.e. crustaceans and molluscs, and fresh water fish. Fish
771 processing is very widespread and varied. Many species of fish are mass processed, including
772 cod, tuna, herring, mackerel, pollock, hake, haddock, salmon, anchovy and pilchards
773 (European Commission, 2006c). Post-harvest loss occurs during pre-processing, processing,
774 storage and transportation of fishery and aquaculture products. Post-harvest fish losses are,
775 for instance, caused by fish scrap generation during fileting, curing and smoking processes
776 and discarding of bycatch at sea because fish is too small or not valuable enough to bring to
777 land for sale. At the global scale, up to **70% of total processed raw fish (on weight basis)**
778 **ends up as solid waste in processing plants** (UNEP, 2000).

779

780 In the EU-28, about 5000 kt of fresh fish is processed on a yearly basis (Eurostat, 2017).
781 Moreover, the EU-28 had a stable output of aquaculture products during the period 2004–
782 2014, with a production quantity fluctuating around 1200 – 1300 kt live weight. Assuming a
783 P content of 0.43% (Hjerne and Hansson, 2002), **the P content of fish residues from**
784 **catches and aquaculture for the EU-28 could amount of up to 27 kt P yr⁻¹**. Moreover,
785 fish excreta and non-digested feed from land-based aquaculture also form a P-source that can
786 potentially be recovered as STRUBIAS materials. Fish residues generated during the
787 processing of raw fish is a great source of minerals, proteins and fat, but if discarded, they
788 can represent a major P loss. Treated fish waste has found many applications among which

789 the most important are animal feed, biodiesel/biogas, dietetic products (chitosan), natural
790 pigments (after extraction) and cosmetics (collagen). Residues from the sector are thus
791 majorly used for the production of value-added products, and off-shore P losses from the
792 sector are estimated relatively small (Hamilton et al., 2016).

793

794 Legally, residues from the fish industry are classified as **animal by-products and derived**
795 **products**. The materials show similarity to animal by-products from the meat and dairy
796 industry, for which reason P-recovery in the form of recovered phosphates, ashes and
797 pyrolysis materials is in theory possible. No industrial STRUBIAS processes of high TRL
798 level have so far been documented by the STRUBIAS sub-group, but similar recovery
799 processes as documented for materials from the meat industry could potentially apply (see
800 paragraph 3.4.3 and 3.4.4).

801

802 3.4.3 Materials from the meat industries

803 **The cattle and poultry industries** are the largest source of animal food industry waste
804 (Jayathilakan et al., 2012; EFPPRA, 2017), with numbers largely exceeding those for fish
805 scrap (Hamilton et al., 2016). In recent years there has been a change in the terminology used
806 to describe outputs from slaughterhouses. The term “by-product” is being used increasingly;
807 in this document, the term "**slaughter residues**" will be used in order to make a clear
808 distinction with other animal by-products, such as manure. Slaughter residues produced in
809 abattoirs consist of the portion of **slaughtered animals that cannot be sold as meat or used**
810 **in meat products**. The consumer has a preference for lean meat, and only limited amounts of
811 organ meats such as brain, kidney, sweetbread, tongue, etc. are consumed. As a result,
812 basically the following residues become available in the slaughter process: (1) edible
813 products such as blood and liver; (2) inedible products such as hair, bones, feathers; (3)
814 manure, contents of rumen and intestines, (4) wastewater, and (5) fat (recovered from the
815 wastewater by means of fat-separators). A complete overview is given in the Reference
816 Document on Best Available Techniques in the Slaughterhouses and Animal By-products
817 Industries (European Commission, 2005).

818

819 Slaughter residues are classified with other **animal by-products according to Regulation**
820 **(EC) 1069/2009**. Slaughter residues are animal derived, and can contain different bacterial,
821 viral, prion and parasitic **pathogens** and cannot be discharged into the environment without
822 proper treatment. Therefore, the use of unprocessed slaughter residues for animal feed has
823 been banned in the EU since 2000 due to fear of Bovine Spongiform Encephalopathy (BSE).
824 Determinate category-specific product **treatment options** should now be undertaken prior to
825 further utilization (Table 3). The rendering industry handles slaughter residues, fallen stock
826 taken from farms, catering waste and unsold animal products that have the potential to
827 become a health risk (EFPPRA, 2017). Through applying the prescribed procedures, rendering
828 makes the material safe and **suitable for reuse** as outlined in the animal by-products
829 Regulation (EC No 1069/2009). The material as obtained after the application of heat and
830 pressure to sterilise and stabilise animal material is rich in fat and protein, for which reason it
831 is suitable for a number of application as outlined in Figure 4. At present, specific animal by-
832 products of category 2 and 3 can be processed and put to further use as feed, organic

833 fertilisers and soil improvers (Article 32 of EC Regulation (EC) 1069/2009 on animal by-
 834 products).
 835

836 **Table 3: Classification of substrates according to Regulation (EC) 1069/2009, and their**
 837 **respective main treatment routes (adopted from Moller, 2015)**

Category 1	Category 2	Category 3
By-products of animals suspected of being infected by TSE (transmissible spongiform encephalopathy) and specified risk materials, including bovine brain and spinal cord.	By-products of animals presenting a risk of infection other than TSE, animals that have died in ways other than being slaughtered, animals killed to eradicate an epizootic disease, and contents of digestive tracts from slaughtering.	By-products arising from the production of goods intended for human consumption using slaughtered animals not affected by any sign of diseases transmissible to humans or other animals. These may also include leftovers from canteens, food processing industry etc.
Material shall optionally be (a) disposed of as waste by incineration (b) recovered or disposed of by co-incineration (c) used as fuel. Very often, the material is incinerated in cement kilns, meaning an irreversible removal of the remaining nutrients P, K, Mg and Ca from the nutrient cycle.	Material can be (a) treated as category 1 material, (b) used for the manufacturing of organic fertilizers following processing by pressure sterilization (e.g. > 133 °C and >3 bars of pressure for >20 minutes), and permanent marking of the resulting material, or (c) composted or transformed to biogas following processing by pressure sterilization.	Material shall be treated (a) as category 1 or 2 material (b) used for manufacturing animal feed after pasteurization (>70°C, >1h), or (c) used for manufacturing organic fertilizers following processing by pasteurization.

838
 839

840 **Poultry** (23 Mt yr⁻¹) and **pig** (21 Mt yr⁻¹) constitute the greatest fractions of animal carcasses
 841 expressed on a weight basis, followed by bovine meat (8 Mt yr⁻¹) (Table 4) (Eurostat, 2016).
 842 Sheep and goat meat do not make up a substantial amount of the slaughtered animals. The
 843 waste fraction is highest for cattle (0.42), than for pig (0.34) and poultry (0.25) (Table 4). **A**
 844 **total amount of 14.5 Mt of slaughter residues** is generated with poultry meat (55%) having
 845 the highest relative contribution, followed by pig (25%) and bovine meat (20%). The data of
 846 Table 5 are generally in agreement with the data as presented by Van Dijk et al. (2016), and
 847 indicate a total P flow of about 281 kT P yr⁻¹ for the sector. Abattoir wastes are characterized
 848 by **very high P contents**. The mean P content of bone for bovine and poultry bone is about
 849 10.5% on a dry weight basis (Beighle et al., 1994; Hemme et al., 2005), and P contents for
 850 blood and offal may reach up to 4.6% and 1.5%, respectively (Gendebien et al., 2001).
 851

852 **Table 4: Overview of the slaughtered animals and the amounts of slaughter residues generated**
 853 **in EU-28 for the year 2005**

	absolute weight of slaughtered animals ^{a,b} (kt yr ⁻¹)	Inedible fraction ^{c,d} (-)	slaughter refuse (kt yr ⁻¹)	relative contribution (%)
bovine meat	8136	0.42	3417	25
calve	946			
adult cattle	6819			
pigmeat	21781	0.34	7405	53
sheep and goat meat	809	0.48	388	3
poultry meat	10797	0.25	2699	19
overall sum	49289		13910	

^abased on Eurostat values for slaughtering in slaughterhouses for the year 2005 (cattle, pig and poultry) and 2015 (sheep and goat)

^bdata for poultry meat are underestimated because data for specific EU Member States are referred to as confidential in the Eurostat database, and could thus not be included

^cincludes the sum of animal fractions that are not transferred to the consumer and food-processing industry

^dbased on EFPR (2017)

854
855

856 Eleven percent of park carcasses, 15% of beef carcasses and 16% of lamb carcasses are **bone**.
 857 With a P content of about 10% (Beighle et al., 1994; Hemme et al., 2005), **this material**
 858 **represents a dominant proportion based of the P present in the non-edible animal by-**
 859 **products**. As a matter of fact, the majority of P (85-88%) exists as bone P in the body of
 860 vertebrates (Hua et al., 2005).

861

862 Also, significant volumes of **waste waters** are produced at the slaughterhouse. This category
 863 contains dung and urine from animal holding areas, washings from distribution vehicles, and
 864 waste water generated during the process of meat and bone meal production (European
 865 Commission, 2005). These waste waters are either treated on-site or discharged to municipal
 866 waste water treatment (European Commission, 2005). The on-site generated waste waters
 867 may have been in contact with category 1 animal by-products. Therefore, the P-recovery
 868 from these waste waters may be legally impeded as the category 1 materials may not be used
 869 for the production of fertilisers according to Regulation (EC) 1069/2009.

870

871

872 3.4.4 Rendering industry

873 Rendering transforms the non-edible materials discarded by the meat and other industries into
 874 stable, value-added materials. Rendering can be carried out on an industrial, farm, or kitchen
 875 scale. The majority of tissue processed comes from slaughterhouses, but also includes
 876 restaurant grease and butcher shop trimmings and expired meat from grocery stores. This
 877 material can include the fatty tissue, bones, and offal, as well as entire carcasses of animals
 878 condemned at slaughterhouses, and those that have died on farms, in transit, etc. The most
 879 common animal sources are beef, pork, sheep, and poultry. The rendering process

880 simultaneously dries the material and separates the fat from the bone and protein. A rendering
881 process yields a fat commodity (yellow grease, choice white grease, bleachable fancy tallow,
882 etc.) and a protein meal (meat and bone meal, poultry byproduct meal, etc.). Rendering plants
883 often also handle other materials, such as slaughterhouse blood, feathers and hair, but do so
884 using processes distinct from true rendering.

885

886 The work of van Dijk et al. (2016) indicates significant P losses of 294 kt P yr⁻¹ from the
887 slaughter residues for the reference year. It should be noted that **these numbers might be**
888 **outdated at present because the entry into force of the EC Animal By-Products**
889 **Regulation** (Regulation (EC) No 1069/2009). Following the crises related to the outbreak of
890 foot-and-mouth disease, the spread of transmissible spongiform encephalopathies such as
891 bovine spongiform encephalopathy (BSE), the further use of animal by-products was largely
892 restricted. The disposal of all animal by-products was, however, not a realistic option as it
893 would lead to unsustainable costs and risks for the environment, and contradicts with the
894 sustainable management of these materials. The clear interest of EU Member States to use
895 animal by-products for a wide range of applications in sustainable manner was reflected in
896 EC Regulation No 1069/2009 as outlined in Figure 4.

897

898 Altogether, the European Fat Processors and Renderers Association (EFPRA) process
899 annually about 17 Mt of material in Europe. **From this 17 Mt, about 12 Mt is classified as**
900 **category 3 materials, about 0.8 Mt as category 2 materials and 4.6 Mt as category 1**
901 **material** (EFPRA, 2017). Given the limited treatment disposal options for category 1 animal
902 by-products, these materials are almost exclusively used for renewable energy production
903 (Dobbelare, 2017) (Figure 4). Category 2 material is mainly used for the production of
904 biodiesel (fat fraction), and fertilisers (protein fraction) (Dobbelare, 2017) (Figure 4). About
905 180 kt of category 2 protein material is used for the production of (organic) fertilisers in the
906 year 2016 (Dobbelare, 2017). The fat fraction of Category 3 animal by-products are typically
907 processed to produce Processed Animal Proteins (PAP), that can be used for pet food, animal
908 feed including and fish feed, oleochemicals, edible fats and biodiesel (EFPRA, 2017). The
909 protein fraction for category 3 material equalled 2.7 Mt of material in 2016, and was
910 dominantly used for the production of pet food (~70%), (organic) fertilisers (18%), and to a
911 smaller extent for fish feed, human food (gelatin) and fur feed (EFPRA, 2017) (Figure 4).
912 About 510 kt of (organic) fertilisers were produced from category 3 material in the year 2016.
913 **Assuming a P content of 5.3% for the protein fraction (Moller, 2015), the current**
914 **fertiliser volumes of category 2 and 3 category animal by-products would equal about**
915 **27 kt P yr⁻¹.**

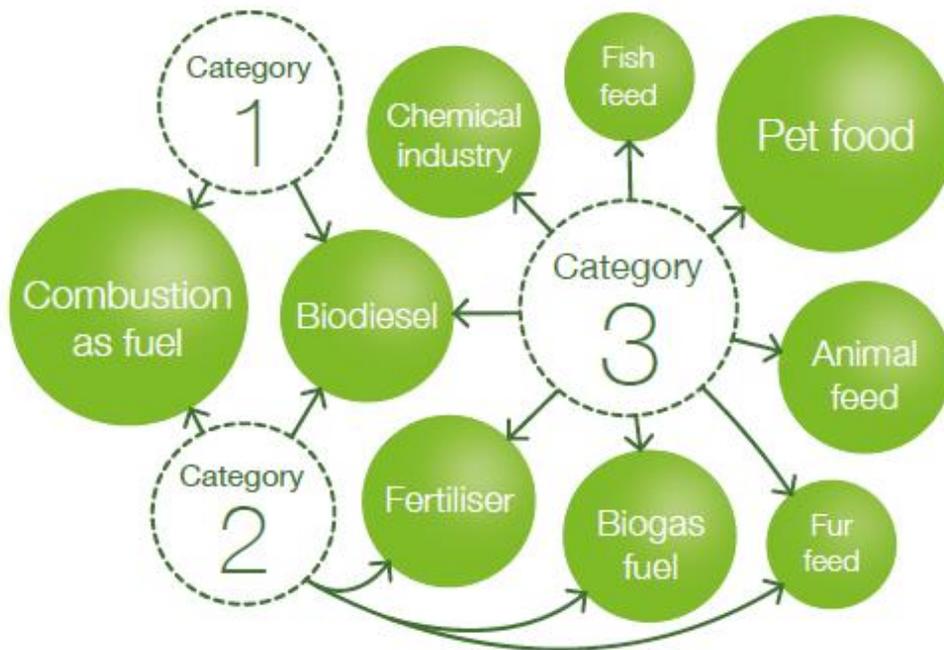
916

917 Time series of the fate of animal by-products for France confirm that the fraction of category
918 3 animal by-products that is incinerated for energy recovery has significantly decreased over
919 the last decade (2006 – 2015), and that the relative share used for pet food production
920 significantly increased (SIFCO, 2017). **It is concluded that the entry into force of**
921 **Regulation (EC) No 1069/2009 effective increased the re-utilisation of animal by-**
922 **products of category 3.** Therefore, the pet food sector is a significant competing industry for

923 the fertiliser industry that produces plant nutrition products from category 3 animal by-
924 products.

925

926 Therefore, the current P fraction that is dissipated is largely restricted to P present in category
927 1 (4.6 Mt material yr⁻¹) that is incinerated for energy recovery or used as biodiesel after prior
928 processing steps.



929

930 **Figure 4: Potential application of processed animal by-products of category 1, 2 and 3 (source:**
931 **EFPPA (2017))**

932

933 Animal by-products other than manure and derived products not intended for human
934 consumption are currently already used for the manufacturing of STRUBIAS materials. The
935 mono-incineration of 1 tonne of animal derived meal and grist generates about 100-300 kg of
936 **ash** (Coutand et al., 2008). During the incineration process, all organic matter in the material,
937 including proteins, is transformed to CO₂, H₂O and nitrous and sulphur oxides, etc. Minerals
938 like Ca, Mg and P are relatively stable in response to heating (Deydier et al., 2005; Zheng et
939 al., 2013). As a result, meat and bone meal ashes have high P (average 14.0%, range 6.1% -
940 18.9%) and Ca contents (20.9%), but low N contents (average 0.17%) (Deydier et al., 2005;
941 Wopenka and Pasteris, 2005; Czaja and Hermann, 2011). The combustion induces a wide
942 range of structural modifications, such as crystallization of calcium phosphate, substitution
943 reactions, etc. These processes reduce the P-solubility and therefore the value of the meat and
944 bone meal ashes as P fertiliser in comparison to the original substrate (Moller, 2015). At
945 present, however, co-incineration is the dominant thermochemical pathway due to the ease of
946 operation and increased energy revenues. Mono-incineration is only applied at specific
947 facilities (e.g. Kalfos – SARIA) that aim at producing meat and bone meal ashes for use as a
948 fertilising material. Bone grist is also the input material for the **production of Animal Bone**
949 **biochar** (3R AgroCarbon, 2016), a fertiliser material with a P content of 13%. **Calcium**
950 **phosphates can be precipitated** when degreasing animal residues (bone) during the
951 demineralisation of the liquor during **gelatine manufacturing**.

952

953 **3.5 Effluents and residues from municipal waste water treatment plants**

954 **Waste water treatment plants** process grey/black water from households and industrial
955 waste water produced. The dominant share of P from **industrial waste waters** present in
956 **industrial sewage** is found in the sludge from the meat industry, potato industry, dairy
957 industries, vegetable industry, and pulp and paper industry (Geertjes et al., 2016), and will be
958 covered is therefore covered in the respective sections.

959

960 Municipal sewage is a **water-carried waste** that is intended to be **removed from a**
961 **community**. It consists mostly of greywater (from sinks, tubs, showers, dishwashers, and
962 clothes washers), blackwater (the water used to flush toilets, combined with the human waste
963 that it flushes away); soaps and detergents; and toilet paper. The Urban Waste Water
964 Treatment Directive (91/271/EEC) defines an **agglomeration** as an area where the population
965 and/or economic activities are sufficiently concentrated for urban waste water to be collected
966 and conducted to an urban waste water treatment plant or to a final discharge point. The size
967 of an agglomeration in terms of generated pollution load is measured in “**population**
968 **equivalent**” (p.e.). This is the organic biodegradable load that has a five-day biochemical
969 oxygen demand (BOD5) of 60 g of oxygen per day, or in more popular terms – the organic
970 biodegradable load generated by one person per day.

971

972 **Sewage treatment** is the process of removing contaminants from wastewater. It includes
973 physical, chemical, and biological processes to remove these contaminants and produce
974 environmentally safe treated wastewater (or treated effluent). **Primary** (mechanical)
975 treatment removes part of the suspended solids, while **secondary** (biological) treatment uses
976 aerobic or anaerobic micro-organisms to decompose most of the organic matter and nutrients
977 (mostly N). **Tertiary** (advanced) treatment removes the organic matter and nutrients even
978 more efficiently. It generally includes P retention and in some cases enhanced N removal.
979 Nitrogen removal is regularly achieved through biological N removal through N reducing
980 pathways (denitrification, possibly Anammox) that **remove the N from the system** as
981 gaseous compounds, although specific recovery options are available (e.g. ammonia
982 stripping).

983

984 The main objective of the **Urban Waste Water Treatment Directive** (91/271/EEC) and
985 national legislation for non-EU countries is to protect surface waters from the adverse effects
986 of wastewater discharges. This is achieved through the **requirement for collection and**
987 **treatment of wastewater** in all settlements (agglomerations) and areas of economic activity
988 with a population equivalent (p.e.) larger than 2000. The connection rate in Central European
989 countries is even higher, and exceeds 90%. About 80% of the population is connected to
990 waste water treatment in Northern and Southern European countries. On the basis of data
991 reported in 2010, about 67% of the total population is connected to wastewater treatment in
992 the countries of Eastern Europe. **Advanced (secondary or tertiary) treatments for nutrient**
993 **and organic matter removal are required for populations larger than 10 000 p.e.** The
994 current population connected to plants with tertiary treatment is in the order of 70% in

995 Northern and Central Europe, and about 50% for Southern and Eastern Europe (European
 996 Environment Agency, 2013b). Average connection rate in South-East Europe (Turkey,
 997 Bulgaria and Romania) is about 40%. About a quarter of the population in South Eastern
 998 countries is connected to collecting systems without treatment (European Environment
 999 Agency, 2013b).

1000

1001 Table 5 shows the generated organic pollution load that agglomerations discharge as a
 1002 function of size class (European Commission, 2017b).

1003

1004 **Table 5: The generated organic pollution load of urban waste water treatment agglomerations**
 1005 **as a function of size class (European Commission, 2017b)**

	Total load discharged from agglomerations 2000-10000 p.e. (million p.e.)	Total load discharged from agglomerations >10000 p.e. (million p.e.)	Total load discharged from big cities discharging >150 000 pe (million p.e.)
EU15	51	457	230
EU13	17	62	47
EU28	68	519	277

1006

1007 Different configurations exist for P removal in waste water treatment plants, with the most
 1008 popular techniques being **enhanced biological phosphorus removal (EBPR)** and **chemical**
 1009 **phosphorus removal (Chem-P)** using Fe or Al salts.

1010

1011 The major feature of the **EBPR process** is that organic matter uptake and P release take place
 1012 under anaerobic condition and P uptake takes place under subsequent aerobic zone (Zhang et
 1013 al., 2013). The enhanced phosphorus removal is attributed mainly to a group of selectively
 1014 enriched heterotrophic bacteria, i.e., **P-accumulating organisms (PAOs)**. PAOs store carbon
 1015 sources as intracellular polymers [i.e., poly- β -hydroxyalkanoates] using the energy of
 1016 polyphosphate (polyP) and glycogen degradation and then release orthophosphate (orthoP)
 1017 into the outside under anaerobic conditions. In the subsequent aerobic phase, PAOs use the
 1018 stored poly- β -hydroxyalkanoates as an energy source, transforming orthoP to polyP,
 1019 replenishing glycogen and self-growth. Phosphorus is accumulated in the sludge and is
 1020 removed by sedimentation and discharging the P-rich excess sludge.

1021

1022 Chemical treatment for phosphorus removal involves **the addition of metal salts** to react
 1023 with soluble phosphate to form solid precipitates that are removed by solids separation
 1024 processes including clarification and filtration. The most common metal salts used are in the
 1025 form of alum (aluminum sulfate), sodium aluminate, ferric chloride, ferric sulfate, ferrous
 1026 sulfate, and ferrous chloride. The chemicals can be added before the primary settling, during
 1027 secondary treatment or as part of a tertiary treatment process. Iron salts are usually preferred
 1028 over Al salts due to their lower cost (Wilfert et al., 2015). Apart from P removal, Fe plays an

1029 important role to prevent hydrogen sulfide emissions during anaerobic digestion and acts as a
 1030 coagulant to improve sludge dewatering (Charles et al., 2006; Ge et al., 2013).

1031
 1032 Chem-P is more prevalent than EBPR in municipal waste water treatment plants in Europe
 1033 (Paul et al., 2001; DWA, 2005; Korving, 2012; Carliell-Marquet and Cooper, 2014; Wilfert et
 1034 al., 2015).

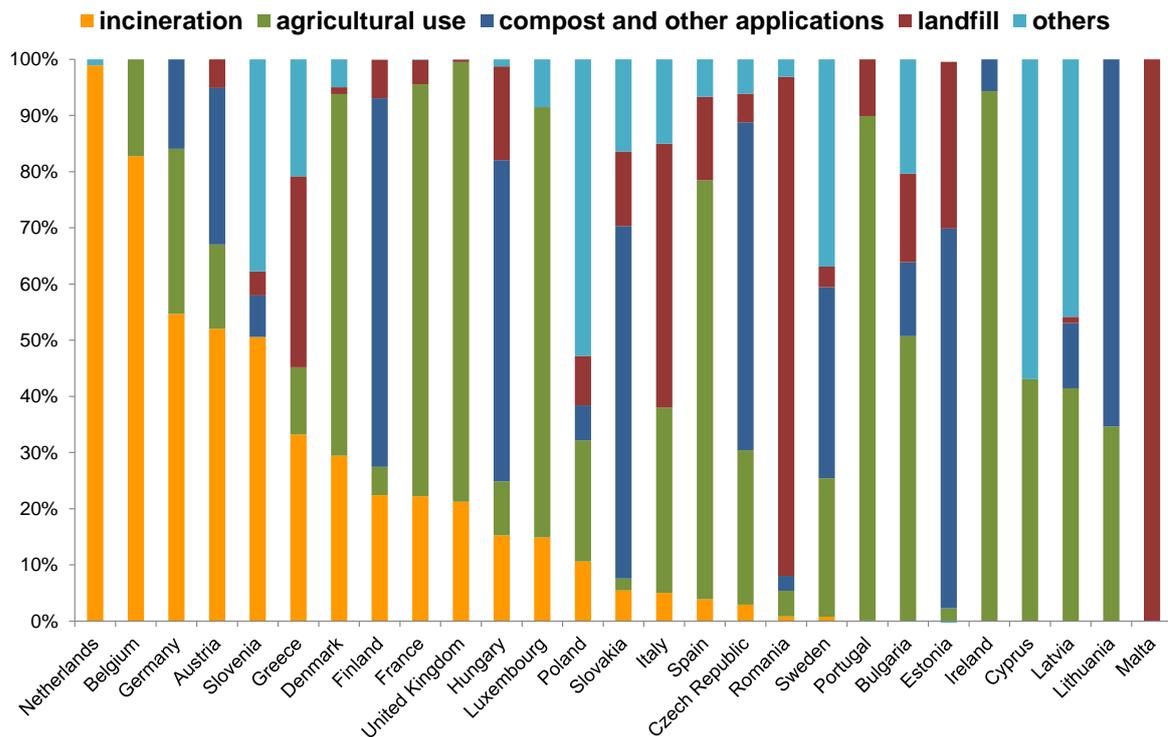
1035
 1036 **Table 6: Configurations used in enhanced phosphorus removal methods used in selected EU**
 1037 **Member States (adopted from Wilfert et al., 2015)**

Country	Type of weighting	No tertiary treatment	Mostly EBPR	EBPR with		Reference
				ChemP support	ChemP	
Germany	People equivalents	2%	6%	31%	61%	DWA, 2015
	Number of plants	20%	16%	21%	43%	
The Netherlands	Sludge production	4%	13%	51%	32%	Korving, 2012
United Kingdom	People equivalents	no data	5%	no data	95%	Carliell-Marquet and Cooper, 2014
	Number of plants	no data	23%	no data	77%	
Germany	Number of plants	no data	17%	36%	47%	Paul et al., 2001

1038
 1039
 1040 Although removal of phosphorus from waste water is a requirement under Article 5 of the
 1041 Urban Waste Water Treatment Directive (91/271/EEC), **this directive does not require**
 1042 **extraction of the P in a useable form.** One particular feature of the Directive is that it allows
 1043 the flocculation of the phosphorus using aluminium and iron, which produces a strongly
 1044 bound compound from which the P is not easily commercially recoverable and which may
 1045 not be fully available to plants (Wilfert et al., 2015).

1046
 1047 **Sewage sludge** is the semi-solid material or slurry that remains after the treatment. Sewage
 1048 sludge is an organic substrate relatively **rich in nutrients, but also might contain a**
 1049 **substantial amount of organic and inorganic contaminants.** The material has to undergo
 1050 further treatment before being suitable for disposal or land application. According to the CEN
 1051 (European Committee for Standardization), sludge is defined as "*a mixture of water and*
 1052 *solids separated from various types of water as a result of natural or artificial processes*". In
 1053 sewage treatment works, **sludge is further treated** to reduce its water content (thickening,
 1054 dewatering, drying, or a combination thereof) and to increase its stability (anaerobic
 1055 digestion, aerobic stabilization, lime stabilization, composting, or a combination thereof).

1056
 1057 The current **fate of treated sludge** includes disposal in landfills, application to land,
 1058 incineration, or composting (Figure 5). Existing national and EU regulation also set
 1059 progressive limits on disposing sludge in landfill and its direct application to land, especially
 1060 in densely populated EU regions (Buckwell and Nadeu, 2016). This has caused an increase
 1061 and interest for **the importance of alternative disposal and recycling routes for growing**
 1062 **amounts of sewage sludge.**



1064
1065 **Figure 5: Routes for sewage sludge disposal in the year 2012 in EU-27 (year 2010 data for**
1066 **Italy) (data available from Eurostat).**
1067

1068 In 2012, about **23% of the sludge is incinerated** in Europe (2.3 Mt dry sludge yr⁻¹),
1069 meanwhile **49%** (5.0 Mt dry sludge yr⁻¹) of the sludge is directly **returned to land for**
1070 **agricultural use** (Eurostat, 2012). Nevertheless, large differences in the proportional
1071 contribution of sewage sludge disposal routes exist among Member States for the fate of
1072 sewage sludge (Figure 5). Countries with a high population and animal density, and strict
1073 restrictions on landfilling, incinerate high proportions of their sewage sludge (e.g.
1074 Netherlands, Belgium, Germany and Austria) (Figure 5). Other Member States (Denmark,
1075 France, United Kingdom, Luxembourg, Spain, and Portugal) apply large amounts of the
1076 sewage sludge directly on land. Finally, Member States as Greece, Italy, Romania, Estonia
1077 and Malta landfill significant amounts of sludge (Figure 5).
1078

1079 Although the Sewage Sludge Directive (91/271/EEC) has established the conditions for safe
1080 use of sludge on agricultural land, but concerns exist, notably as regards the maximum limit
1081 values for cadmium and other contaminants are considered to be too high (European
1082 Commission, 2013a). Sixteen Member States have adopted more stringent standards than
1083 those set out in the Directive. **Therefore, direct sewage sludge application on agricultural**
1084 **land is progressively decreasing in Europe.** Harmonisation of higher quality standards
1085 would encourage greater confidence amongst farmers and consumers on the safe use of
1086 sludge in the EU. In order to encourage more efficient resource use in the future, these issues
1087 will need to be addressed so that standards for sewage sludge-derived products inspire
1088 confidence right across the chain of end users: namely farmers, retailers and ultimately
1089 consumers.

1090
1091 A **detailed description of the sewage sludge mono-incineration process** is given in
1092 Donatello and Cheeseman (2013). Sludge and hot compressed air (ca. 500–600°C) are fed to
1093 the combustion chamber. The sand bed temperature is typically 750°C and the overhead
1094 freeboard zone at 800–900°C. Temperatures can be finely controlled by the injection of water
1095 or liquefied gas oil. The sand bed acts as a “thermal fly wheel” and helps stabilise
1096 temperature fluctuations in the incinerator. Particle residence times in the combustion
1097 chamber are typically only 1–2 s and during this time water is evaporated, volatile metals
1098 vapourise and organic compounds are combusted completely to gases, either directly or via
1099 the formation of an intermediate char. The remaining inorganic material is carried out of the
1100 chamber as fine particulates with the exhaust gases. During incineration, **most of the N is**
1101 **released into the atmosphere while much of the P and K, and heavy metals are retained**
1102 **in the fly ash** (Deydier et al., 2005; Zheng et al., 2013). Sulphur (S) is retained in the air
1103 pollution system, and can possibly be recycled as Na₂SO₄ from the alkaline scrubber. The fly
1104 ash is generally removed by bag filters, electrostatic precipitators or cyclones after passing
1105 through a heat exchanger. The flue gas is then treated using a wet scrubber with acid, alkali
1106 and possibly activated carbon dosing to comply with emission limits, as required by
1107 Industrial Emissions Directive (2010/75/EU). The scrubbing process produces an additional
1108 waste sludge, which is dewatered and normally disposed of in hazardous waste landfill.
1109 **Mono-incineration produces fly ash with high P contents (2-12%)**. The average P content
1110 in sewage sludge ashes is 10.8 % in the Netherlands (CBS Statistics Netherlands, 2015) and
1111 8.9% in Germany (Krüger and Adam, 2015). In Germany, about half of the generated
1112 municipal sewage sludge is currently already processed within mono-incineration plants
1113 (Adam et al., 2015).

1114
1115 Sludge can also be **co-incinerated with municipal solid waste or industrial waste** in
1116 existing general purpose incineration plants that produce energy. The ash produced has a
1117 lower P concentration (e.g. on average 4.9% in Germany), and potentially a higher amount of
1118 impurities and contaminants.

1119
1120 In the EU-28, it is estimated that annually generated municipal waste waters contain **2.3-3.1**
1121 **Mt of N and around 0.50 Mt of P** (Sutton et al., 2011; Leip et al., 2014; van Dijk et al.,
1122 2016). About 227 kt P yr⁻¹ ends up in communal sewage sludge, and an additional 74 kt P yr⁻¹
1123 is lost as effluents from urban and decentralised waste water treatment plants. Untreated and
1124 uncollected waste waters sum up a total of about 59 kt P yr⁻¹. The remainder 140 kt P is
1125 contained in sewage sludge that is directly applied on agricultural land.

1126
1127 **STRUBIAS materials can be produced from (processed) wastewaters and sludges at**
1128 **municipal waste water treatments plants, as well from the incinerated sewage sludges**
1129 (see section 4).

1130
1131

1132 3.6 Food processing industry residues other than animal by-products

1133 Three different food processing sectors, other than the meat and fish industry, have been
1134 identified that show a discernible potential for P-recovery. Losses from food processing
1135 industries correspond to **44 kt P and 157 kt N per year** (Sutton et al., 2011; van Dijk et al.,
1136 2016). The share of P can be split up in losses in solid forms (e.g. sludges: 36 kt P) and losses
1137 as wastewaters (9.2 kt P). Currently, **P is recovered in the form of recovered phosphate**
1138 **salts from the wastewaters from the potato and dairy industry**. Given that the sludges are
1139 characterised by high moisture but low P contents, supplementary STRUBIAS recovery from
1140 the sludges will most likely be in the form of recovered phosphate salts, eventually after
1141 anaerobic digestion of the residues.

1142

1143 3.6.1 Potato crisps and chips industry

1144 Two of the main potato-based products are crisps and chips. The manufacturing of both
1145 essentially consists of peeling the raw material, slicing to an appropriate size and blanching,
1146 followed by frying to achieve the desired sensory properties. To prevent colourisation of the
1147 potato, a substance **called pyrophosphate** ($\text{Na}_2\text{H}_2\text{P}_2\text{O}_7$) is used to complex iron (Fe^{2+}). In
1148 this way sodium acid pyrophosphate prevents that iron in the potato reacts with chlorogenic
1149 acid during the heating processes (Rossell, 2001). The oxidation of the Fe^{2+} -chlorogenic acid
1150 complex by oxygen from the air would otherwise result into a grayish-colored substance that
1151 causes the after-cooking gray discoloration (Rossell, 2001). This is a very significant P-
1152 source in the waste water from potato processing installations. The waste water have a typical
1153 PO_4^{3-}P concentration of about 200 mg L^{-1} (European Commission, 2017c). **Average P-**
1154 **recovery efficiencies of 80–90% have been reported**. The cost of recovery is lower
1155 compared to phosphorus removal by chemical precipitation using, for example, FeCl_3
1156 (European Commission, 2017c). At present, more than 4 t of struvite per year is produced by
1157 the potato-processing in Belgium and the Netherlands (Dewaele, 2015).

1158

1159 3.6.2 Waste waters from the dairy, brewery, grain, fruit and vegetable industry

1160 Plant-derived waste arises from cultivated grains, fruits, and vegetables. A determined
1161 fraction of the plant materials are not edible and are thus treated as agrowaste. Spillage,
1162 spoilage and storage loss or outgrading, pest infestation, and loss of quality during storage
1163 can be the main reasons for loss of agricultural produce after harvesting. Additional waste is
1164 generated during processing stages such as peeling, washing, boiling, and slicing. Finally,
1165 byproducts such as pomace and spent grain are formed, and wastes from plant shutdowns or
1166 washing occur (de las Fuentes et al., 2003).

1167

1168 **Water consumption** is one of the key environmental issues for the food processing sector.
1169 Dairy and brewery industries are major water consumers, producing waste waters that are
1170 generally not dangerous but are heavily loaded with organic matter (Gendebien et al., 2001).
1171 The composition of the effluents is quite variable in composition. Compared to effluents from
1172 the chips and crisp industry, dairy, brewery and starch manufacturing industries have –
1173 generally speaking - less P in their waste waters.

1174

1175 A significant proportion of the waste waters are originating from the washing of installations.
1176 Typical **cleaning agents** used in the food-processing industry sector are (European
1177 commission, 2006b):

- 1178 • alkalis, e.g. sodium and potassium hydroxide, metasilicate, sodium carbonate;
- 1179 • acids, e.g. nitric acid, phosphoric acid, citric acid, gluconic acid;
- 1180 • pre-prepared cleaning agents containing chelating agents such as EDTA, NTA,
1181 phosphates, polyphosphates, phosphonates or surface-active agents;
- 1182 • oxidising and non-oxidising biocides.

1183 The use of chelating agents and biocides may hamper nutrient recovery as the contaminants
1184 may be transferred to the recovered material.

1185

1186 Many **dairies** use large amounts of water, mainly for cleaning. The PO_4^{3-}P concentration in
1187 the waste water varies between 20 and 200 mg L^{-1} (European commission, 2006b). Many
1188 dairies have built their own effluent treatment plant and produce large amounts of sludges
1189 rich in P and organic matter. Humana Milchunion E.G. has installed a struvite reactor to
1190 recover P from dairy wastewater effluents (PO_4^{3-}P concentration in the waste water: 60 – 65
1191 mg P L^{-1} ; P-recovery efficiency of about 75%).

1192 In the **brewery**, waste water from the anaerobic reactor is driven to a reservoir where it is
1193 mixed with aerobic sludge (from the second sedimentation) and with untreated neutralised
1194 waste water (taken before anaerobic digestion). The PO_4^{3-}P concentration in the waste water
1195 varies between 0 and 200 mg L^{-1} (Gendebien et al., 2001). All these flows are recirculating
1196 and, in these conditions, the aerobic sludge encourages the growth of P-assimilating bacteria.
1197 Phosphorus could then be recovered after the bacterial release of orthophosphates.

1198 **Sugar mills** produce wastewater, emissions and solid waste from plant matter and sludge
1199 washed from the sugar beet (Hess et al., 2014). Sugar beet is 75% water, and the extraction
1200 process, by definition, aims to release a high proportion of water contained in the beets. The
1201 technique applied for sugar extraction from plant tissues has an impact on the volumes of
1202 water used (consumed and polluted) to produce sugar (Bio Intelligence Service -
1203 Umweltbundesamt - AEA, 2010). Considering the high nutrient contents of the sugar beet,
1204 the waste generated during the sugar beet processing is also rich in N and P (Buckwell and
1205 Nadeu, 2016). Gendebien et al. (2001) indicated, for instance, effluent P concentrations of >
1206 100 mg P L^{-1} .

1207

1208

1209 **3.7 Chemical industry waste waters**

1210 The EU chemical industry sector provides a significant contribution to the EU economy. It is
1211 one of its most international and competitive industries, connected to a wide field of
1212 processing and manufacturing activities (European commission, 2014). **Specific chemical**
1213 **industry subsectors are responsible for the most significant emissions of macronutrients**
1214 **to water, especially P** (E-PRTR, 2013; European commission, 2014). Emissions of P to
1215 water by the chemical industry sector equal a total of **10.3 kt P** for the year 2010. The
1216 dominant contribution originates from **manufacture and formulation of pharmaceutical**

1217 **products** (9.41 kt P), with only a minor share from other chemical industries such as basic
1218 organic chemicals (0.45 kt P), basic inorganic chemical (0.32 kt P) and fertilisers (0.12 kt P)
1219 (E-PRTR, 2013; European commission, 2014).

1220
1221 Pharmaceuticals are produced using synthesis or fermentation. Organic wastes produced in
1222 the pharmaceutical industry are mainly **biomass** (cells from the fermentation process),
1223 **synthesis residues, alcohol and organic solvents** from the cleaning process, product
1224 residues and dust from reprocessing (Gendebien et al., 2001). Care has to be taken where
1225 residues originate from the pharmaceutical industry as it is very **difficult to fully remove**
1226 **traces of the pharmaceutical end product and hazardous solvents from the waste**
1227 **waters**. Aqueous wastes from the from the manufacture, formulation, supply and use
1228 (MFSU) of pharmaceuticals is classified as hazardous waste according to the European List
1229 of Waste pursuant to Directive 2008/98/EC.

1230
1231 At present, Genzyme bvba makes use of a struvite reactor for P-recovery in the form of
1232 recovered phosphate salts from their pharmaceuticals production plant in Geel, Belgium. The
1233 P-rich wastewaters (55 mg $\text{PO}_4^{3-}\text{-P}$) are used for the production of 220 kg of struvite
1234 (Dewaele, 2015).

1235
1236

1237 **3.8 Iron and steel industry residues**

1238 Steelmaking slags are residues of processing molten iron into a specific type or grade of steel
1239 (Reijonen, 2017). Today there are two major commercial processes for making steel, namely
1240 **basic oxygen steelmaking**, which has liquid pig-iron from the blast furnace and scrap steel
1241 as the main feed materials, and **electric arc furnace steelmaking**, which uses scrap steel or
1242 direct reduced iron as the main feed materials. The slags are often referred to by the type of
1243 furnace: blast furnace slag, blast oxygen furnace slags and electric-furnace slags. Nowadays,
1244 basic oxygen steelmaking and electric arc furnaces account for virtually all steel production
1245 (Jewell and Kimball, 2014). On average the production of one tonne of steel results in 200 kg
1246 (electric arc furnace steelmaking) to 400 kg (basic oxygen steelmaking) of residues. These
1247 include slags, dusts, sludges and other materials.

1248
1249 **Blast oxygen furnace slag** is formed in the basic oxygen converter during the conversion of
1250 pig iron into crude steel. In this process, molten metal from blast furnace is treated with
1251 oxygen to remove impurities via oxidation at 1400–1650 °C (Yildirim and Prezzi, 2011).
1252 Oxidation is followed by slag formation with burned lime. The principal components of both
1253 slags are silicates, aluminates and oxides of Ca, or to lesser extent of Mg (Waligora et al.,
1254 2010). **Granulated blast furnace slag** is formed in the smelting process of iron ore/pellets
1255 with coke and flux (limestone, burned lime or dolomite). Silicate and aluminate impurities in
1256 the ore and coke are chemically bound to lime (CaO), and then removed as a molten slag. Oil,
1257 tar, natural gas, powdered coal and oxygen can also be injected into the furnace to combine
1258 with the coke to release additional energy which is necessary to increase productivity.
1259 **Electric arc furnace slag** is produced when scrap metal and fluxes are oxidized by the use of

1260 an electric current. Chemical energy is supplied via several sources including oxy-fuel
1261 burners and oxygen injections. Oxy-fuel burners combust natural gas using oxygen or a blend
1262 of oxygen and air. In some operations, oxygen is injected via a consumable pipe lance to
1263 "cut" the scrap. The oxygen reacts with the hot scrap and burns iron to produce intense heat
1264 for cutting the scrap. Once a molten pool of steel is generated in the furnace, oxygen can be
1265 lanced directly into the bath. This oxygen will react with several components in the bath
1266 including, aluminum, silicon, manganese, phosphorus, carbon and iron. All of these reactions
1267 are exothermic and thus supply additional energy to aid in the melting of the scrap. The
1268 metallic oxides that are formed will end up in the slag.

1269
1270 Slags that have undergone **a thermal oxidation at high temperatures** could be considered
1271 **as ash-based materials in the STRUBIAS project**. At present, approximately 800 000
1272 tonnes of these slags are used as **fertilising products within the EU, mostly in the form of**
1273 **liming materials and P-rich slags that are used as fertilisers**.

1274
1275

1276 **3.9 Forest-based industry residues and green waste**

1277 3.9.1 Woody residues

1278 This category includes woody residues that originates from (1) **sidestreams produced by the**
1279 **woodworking industry** for instance harvest slash, sawmill sidestreams and shavings from
1280 timber yards, materials from chipboard and other timber processing, reclaimed timber from
1281 buildings, pallets and packing crates, (2) currently **uncollected forest residues** and (3) the
1282 processing of plant materials other than residues **from households waste** classified as food
1283 waste (including parks and garden waste).

1284

1285 The **total amounts of wood residues** that are available within the EU for posterior use are
1286 **estimated at about 120 Mt per year**, with future predictions remaining more or less at the
1287 same level (Searle and Malins, 2013). This number is the sum of following fractions:

1288 • According to Manteau (2012), **26 million tonnes of post-consumer wood** (i.e. wood
1289 products such as furniture that are discarded) was generated in 2010. Of this, 7.8
1290 million tonnes was recycled into other materials and 10.3 million tonnes was burned
1291 for energy in power plants or households. About 8 million tonnes was permanently
1292 disposed of or incinerated without energy recovery.

1293 • Forests and other wooded land occupy over 44% of the EU's surface and represent 5%
1294 of the world's forests. In the last 50 years, both their area and the standing timber
1295 volume (growing stock) have continued to grow. Nowadays, they gain almost 700 000
1296 ha annually. According to Searle and Malins (2013), it was estimated that the total
1297 production of **forestry residues in the EU was 80.7 million tonnes** in 2011. Some
1298 forestry residues are currently collected, but according to ECF (European Climate
1299 Foundation, 2013), the current usage of forestry residues in the EU is only about 3%,
1300 with activities mainly occurring in Scandinavia. Similar to crop residues, a share of
1301 the forestry residues should remain on land to protect soil carbon and sustainable

1302 ecosystem functioning. To be conservative and to avoid other unintended
1303 consequences, Searle and Malins (2013) assumed that **50% removal of forestry**
1304 **residues may be sustainable** if combined with good management practices.
1305 Assuming these values, a total of about 40 million tonnes of uncollected forestry
1306 residues might potentially be available for nutrient recovery.

- 1307 • Presumably much of the 19.7 million tonnes of **household vegetal waste are garden**
1308 **clippings and other wood residues** (Searle and Malins, 2013).

1309

1310 Wood **treated** with preservative chemicals such as pentachlorophenol, lindane or copper
1311 chrome arsenate **may hinder its posterior use**, including recycling and energy recovery.
1312 **Untreated wood waste is a material with high organic matter content, but with a**
1313 **relatively low nutrient content**, both in terms of N (often < 1%) and P (~0.1%). Gendebien
1314 et al. (2001) indicated an average P content of 0.09%, but no numbers were given for N.
1315 Wood N/P contents vary between 10 and 28 (Mooshammer et al., 2014; Sardans and
1316 Peñuelas, 2015), for which we estimate assume an N content of 1.5%. The high C/N ratio
1317 makes it an unsuitable material for direct fertiliser applications as it will promote microbial N
1318 immobilization and thus reduce the N availability in the soil. It may, nevertheless, be used as
1319 a mulch to discourage weed growth and conserve moisture or as an aggregate for compost.
1320 The total nutrient content of forest residues can then be calculated by multiplying
1321 abovementioned numbers on forest residue availability with the assumed nutrient contents.
1322 Assuming an estimated moisture content of 25-50%, 900 – 1350 kt N and 54-81 kt P yr⁻¹.
1323 These numbers are generally in line with the estimated P-content of **76 kt P as estimated** by
1324 Van Dijk et al. (2016).

1325

1326 Bark and wood residues from wood handling is **normally incinerated for energy recovery**.
1327 Wood ash from bark boilers contains nutrients taken from the forest with the wood raw
1328 material and this ash can be suitable as a fertiliser as long as it is not contaminated, e.g. by
1329 metals like Hg, Cd and Pb. Wood biomass is used for energy production in many EU Member
1330 States, especially in northern Europe. Wood combustion in Denmark, Finland and Sweden
1331 generate >290 kT of biomass ashes, whereas the combined wood ashes of Austria, Germany,
1332 Ireland, Italy and the Netherlands add another 300 kT of wood ashes (van Eijk et al., 2012).
1333 Assuming a P content of 0.1%, the **wood bottom and fly ashes in these European**
1334 **countries thus contain only 0.3 kT of P**. Moreover, competing uses (concrete industry, fill
1335 and ground remediation) exist for these biomass ashes (van Eijk et al., 2012).

1336

1337 Given their high carbon content, wood residues are mainly used for energy production, but
1338 the combustion residues (mainly bottom **ashes**) are often applied on (forested) land in north
1339 European countries (Insam and Knapp, 2011). Wood material is currently also the **dominant**
1340 **input materials for the production of pyrolysis materials** that are used as soil improver
1341 (EBC, 2012).

1342

1343 3.9.2 Pulp and paper industry

1344 For a complete overview of the processing of woody material and recovered materials, it is
1345 referred to the Best Available Techniques (BAT) Reference Document for the Production of
1346 Pulp, Paper and Board (European Commission, 2015a).

1347
1348 The production process used in papermaking depends on the stock used to generate the fibre
1349 (Gendebien et al., 2001). When virgin wood fibre is used to produce **paper**, the pulp creates
1350 liquid effluent and the **sludge** mainly contains lignin and cellulose. When waste paper is used
1351 in the process, de-inking and bleaching is required, and the de-inking sludge will contain
1352 chemical residues. The process of reusing fibre from recycled paper produces large amounts
1353 of sludge (1 tonne of sludge for every tonne of paper produced) (Gendebien et al., 2001). De-
1354 inking sludge will also contain high levels of carbon, calcium carbonate and, generally,
1355 aluminium silicate (Gendebien et al., 2001). Within the paper industry, the most economic
1356 choice for sludge disposal can determine the process used (Gendebien et al., 2001).

1357
1358 All pulp and paper sludge comprises a mixture of cellulose fibre (40 to 60% of dry solids),
1359 printing inks and mineral components (40 to 60% dry solids: kaolin, talc, and **calcium**
1360 **carbonate**). The abundance of metals in the sludges has significantly decreased over the last
1361 decades because legislation that constrains the metal/metalloid content of the ink has
1362 significantly. The P content of the pulp and paper industry sludges is however relatively low
1363 (0.3% P on average; Gendebien et al., 2001).

1364
1365 The **incineration of the sludges** from the dissimilar paper producing processes (Kraft
1366 pulping process, sulphite pulping process, mechanical and chemimechanical pulping process,
1367 and processing of paper from recycling) is a commonly applied process in the sector. The use
1368 of auxiliary fuel may be necessary to maintain good burning conditions unless the sludge is
1369 mixed with bark and other wood waste material. Burning reduces the volume of waste and
1370 the **inorganic content remains as ash**. It is noted that specific effluents cannot be sent for
1371 incineration as a consequence of the use of certain chemicals (e.g. chlorine dioxide).

1372
1373 The **sector BAT conclusions** indicate that the recovery of energy by incinerating wastes and
1374 residues from the production of pulp and paper that have high organic content and calorific
1375 value is permitted on condition that the recycling or reuse of wastes and residues from the
1376 production of pulp and paper is not possible (European Commission, 2015a).

1377
1378 3.9.3 Emissions to water

1379 Liquid effluents contain material in colloidal or suspended forms and dissolved substances.
1380 With few exceptions (eucalyptus pulping), **the original levels of N and P are low and are**
1381 **added to biological waste water treatment plants to feed the biomass**.

1382
1383 3.9.4 Conclusion

1384 From an economic point of view, **the cost of harvest, transport, and processing is**
1385 **disproportional in relation to the P quantities that can be recovered**. Therefore, it is more
1386 likely that any P-recovery from **wood will be formed as part of cascades where synergies**

1387 exist between the manufacturing of other products (energy, paper) and nutrient
1388 recovery.

1389

1390

1391 **3.10 Municipal solid waste**

1392 About **258 Mt of municipal solid waste** (MSW) is produced yearly in the EU-27 (Eurostat,
1393 2016). The N and P of the biodegradable waste fractions mainly originate **food waste and**
1394 **woody residues**. Also some N could be present in textile materials. The biodegradable
1395 fraction represents on average 37% of all municipal solid waste, although the fraction varies
1396 widely between EU countries (European Commission, 2010b).

1397

1398 Municipal solid waste raises problems since it is a **mixture of materials that are**
1399 **heterogeneous in nature and not segregated**. The composition of MSW varies regionally,
1400 but usually contains a mixture of organic waste, paper and cardboard, textile waste, plastics,
1401 metals, glass and potentially some biomedical waste and hazardous (battery, nail polish
1402 bottles, insecticides) compounds (Sokka et al., 2004; Chandrappa and Das, 2012).

1403

1404 A MSW can undergo a **mechanical sorting** of the waste into a biodegradable material
1405 containing fraction and a non-biodegradable material containing fraction. In the latter case,
1406 nutrient recovery from the biodegradable fraction is possible through composting and
1407 anaerobic digestion.

1408

1409 In the alternative scenarios, the MSW is not separated and may either be **landfilled** (resulting
1410 in a complete loss of the material, including its nutrients) **or incinerated**.

1411

1412 **The ashes from MSW** generally contain relatively **low amounts of P**, with values of
1413 approximately 0.4% P (Kalmykova and Fedje, 2013).

1414

1415

1416 **3.11 Others**

1417 Abovementioned input material represent the overall share of the nutrients present in waste
1418 and have therefore the greatest potential for nutrient recovery options. **The STRUBIAS sub-**
1419 **group did not identify waste materials, industrial residues or biological materials other**
1420 **than those mentioned in sections 3.2 - 3.9.**

1421

1422 Nevertheless, other streams originating from secondary raw materials are not de facto
1423 excluded as STRUBIAS input materials. Based on detailed information provided from EU
1424 Member States, Gendebien et al. (2001) provides an excellent, though somewhat out-dated,
1425 overview of the mass amounts, nutrient contents and environmental concerns and health
1426 issues for numerous other waste streams that are currently spread on agricultural land:
1427 **tannery sludge, decarbonation sludge, inorganic waste from chemical industry, textile**
1428 **waste, wool scourers waste, waste lime from cement manufacture or gas processing,**
1429 **waste gypsum, waste from energy production and dredgings.**

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It should be noted that some of these streams (e.g dredgings, waste lime, and waste gypsum) may **contain large amounts of biological contaminants and high amounts of heavy metals** that may potentially hinder nutrient recovery processes. Therefore, treatment may require a potentially large chemical and electrical demand in order to recover a relatively small amount of nutrients from the waste stream. Others streams may be suitable for use as such, in case they are low in contaminants identified.

3.12 Conclusion

Understanding the **complex flow of nutrients throughout the food and non-food production and consumption chains** in Europe is needed **to assess the feasibility and impact potential of different waste streams as input material** for fertilisers derived from secondary raw materials. The overview presented in this document builds further upon the information presented by the scientific community, multi-stakeholder research platforms, think tanks and international and non-governmental organizations (Sutton et al., 2011; Leip et al., 2014; Buckwell and Nadeu, 2016; van Dijk et al., 2016), complemented by own estimates as described in each of the input material sections.

STRUBIAS materials are currently produced from all listed input materials, but the deliberateness of nutrient recovery varies between the different materials. A nutrient recovery system can specifically be designed for nutrient recovery, with the aim:

- to produce **plant nutrition materials from secondary raw materials**: all processes;
- **to avoid the loss or spillage of nutrients into the environment**: manure, effluents and residues from municipal waste waters, food processing residues, residues from gelatin production process;
- to **remove nutrients for improved functioning of biological waste water treatment plants**;

STRUBIAS materials can also be produced – with or without process adaptation - as a primary product or residue of a production process **aimed at the production of a different primary output: energy**, poultry litter ashes, forest-based industry residues, iron and steel industry residues.

Note that some STRUBIAS materials can be listed under different items because the production process can serve different goals and benefits at a time.

1467 4 Production processes and techniques

1468 4.1 Recovered phosphate salts

1469 4.1.1 Waste water treatment plants

1470 In **conventional wastewater treatment** plants, **P** is mainly **eliminated** by **enhanced**
1471 **biological phosphorus removal (EBPR)** or by **chemical precipitation with metal salts**
1472 **(ChemP)** or a combination of both. With EBPR, microorganisms (P accumulating organisms,
1473 PAOs) incorporate P in a cell biomass compound called polyphosphate and the P is removed
1474 from the process by sludge wasting. Chemical precipitation with metal salts can remove the P
1475 to low levels in the effluent. The commonly used chemicals are aluminum (Al(III)), ferric
1476 (Fe(III)), and calcium (Ca(II)). The direct use of P-rich sludge as a fertiliser is associated to
1477 an increasing number of concerns due to concerns related to pathogens, and uncertainties
1478 related to P bioavailability (Cox et al., 1997; Vaneeckhaute et al., 2016).

1479
1480 Phosphate salts can be recovered from **sludge liquor** and from **digested sludge** when the
1481 PO_4^{3-} precipitates together with Mg^{2+} or Ca^{2+} , possibly also trapping NH_4^+ and/or K^+ in the
1482 molecular structure. Struvite, the most commonly recovered phosphate salt, forms from
1483 equimolar quantities of Mg^{2+} , PO_4^{3-} and NH_4^+ implying that the efficiency of NH_4^+ removal
1484 is relatively low and the excess N remains in soluble form. In most sewage treatment
1485 applications **Mg is the limiting element**, for which it is added to the process as MgCl_2 or
1486 MgO . The formation of precipitates is strongly influenced by pH, hence if the feed stream
1487 does not have sufficient alkalinity, NaOH is added and/or CO_2 is stripped from the solution.
1488 More detailed information on the crystallization dynamics and kinetics for the struvite
1489 crystallization process is given in Le Corre et al. (2009).

1490
1491 Phosphorus recovery from sludge liquor and from digested sludge is limited to the amount of
1492 **soluble PO_4^{3-}** . For most waste water treatment plants, the latter is in the range of **5-20% of**
1493 **total P** load of the sludge under normal pH conditions (Jossa and Remy, 2015). P content of
1494 the solid phase can be substantially mobilized into the liquid phase by **acidification** (addition
1495 of acids or through the generation of carbonic acid from pressurised CO_2) or **thermal**
1496 **hydrolysis** so that total P recovery rates of **up to 50%** seem feasible in both pathways.

1497
1498 **Recovery in the form of phosphate salts without acidification treatment** is essentially
1499 **applicable to those wastewater treatment plants where EBPR is used**. Here, the
1500 polyphosphates stored in the bacterial cells are partly released again under anaerobic
1501 conditions, thereby significantly increasing the PO_4^{3-} -P content in the sludge system to levels
1502 that support P recovery. The P content in wastewater treatment plants with EBPR and
1503 anaerobic digestion can be $75\text{--}300 \text{ mg L}^{-1} \text{ PO}_4^{3-}\text{-P}$ after the anaerobic digester (García et al.,
1504 2012).

1505
1506 **P-recovery processes that include** an acidification step are in principal able to deal with
1507 sludge that had been subjected to chemical removal and coagulation with Al and Fe salts.
1508 Nevertheless, when ChemP sludge is used as input material, the **P-recovery rates are**

1509 **reduced or require substantially** larger additions of **chemicals** used in the process (Kabbe
1510 et al., 2015).

1511
1512 **Four types of recovered phosphate forming processes** are considered: (I) from the sludge
1513 liquor, (II) from the digested sludge, (III) downstream from the digested sludge after a pH
1514 regulating treatment, (IV) upstream from the digested sludge with thermal hydrolysis. The 4
1515 types differ in their P-recovery rate, sludge input materials that be used, and energy and
1516 chemical demand (Table 7). For phosphate salt formation from the **liquor** (type I), the
1517 **concentrated side streams** after the anaerobic treatment or the dewatering unit after
1518 anaerobic digestion are the best options for P recovery. The implementation of a P-recovery
1519 system **before the anaerobic digester** (type II and type IV) reduces uncontrolled P
1520 precipitation in the anaerobic digester or post-digestion processes and enhances P recovery
1521 (Martí et al., 2008; Martí et al., 2010). Downstream P recovery from the **sludge phase** can
1522 include recovery from both the digester sludge before and after the dewatering unit.

1523
1524 **Table 7: Overview of the principles and properties of recovered phosphate salt producing**
1525 **processes from waste water treatment plants (adapted from Jossa and Remy (2015)).**

	type I	type II	type III	type IV
	liquor precipitation	sludge precipitation	downstream sludge leaching after acidification	upstream sludge hydrolysis
implementation status	mostly operating, some piloting	operating	operating (Seaborne), piloting (Stuttgarter)	operating
input material	sludge liquor from EBPR	digested sludge from EBPR	digested sludge from EBPR and ChemP	digested sludge from EBPR
phosphorus recovery	low to moderate (~ 11-12%)	low (~ 7%)	high (~ 45-49%)	moderate to high (no exact data)
chemical demand	low	moderate	high	moderate
energy demand	low	low	high	high
increased sludge dewaterability	no	yes	no	yes

1526
1527 ○ Type I: liquor precipitation. Recovered phosphates, mostly struvites, can be
1528 formed **from the sludge liquor in mixed stirred tanks**. The *PHOSPAQ*® and
1529 *ANPHOS*® processes operate in a single and two separate stirred tank reactors.
1530 An increase in pH (CO₂ stripping) and mixing are obtained via aeration, and MgO
1531 is added to the wastewater. The *NuReSys*® process differs from the *ANPHOS*®
1532 process since it is operated in continuous mode instead of batch, at a lower
1533 residence time. Another difference is the use of a different Mg source (MgCl₂) and
1534 the addition of a 29% NaOH solution to the crystallization reactor. The *Struvia*®
1535 process relies on the use of a continuous stirred tank reactor with integrated
1536 solid/liquid separation by calming zone and lamellar packing or with additional
1537 lamella settler. Also the *Phorwater*® and *Prisa*® technologies rely on the struvite

1538 crystallization in a continuous liquid flow system. In the PHORWater® process
1539 the elutriation of the mixed sludge (primary and EBPR sludge) allows reducing
1540 the P load entering the anaerobic digester and achieving a high P concentration in
1541 the supernatant of the sludge thickener (Martí et al., 2010; Bouzas et al., 2016). In
1542 the *Ekobalans*® (pilot) plant, struvite precipitation is a simple, low-cost process
1543 which produces microcrystals that are separated out using hydrocyclones. The
1544 struvite microcrystals are then formulated into dry, regular granules in combination
1545 with (NH₄)₂SO₄ and K salts, to give a NPK fertiliser adapted to agricultural use.
1546 Some processes (*PhosphoGreen*®, *Naskeo*®, *Crystalactor*®, *Rephos*®, and
1547 *Ostara Pearl*®) apply a controlled chemical crystallization in a **fluidized bed**
1548 **reactor to form struvite from the sludge liquor**. Fluidised bed reactors contain a
1549 bed of granulated struvite or fine sand, which acts as a seed material for crystal
1550 growth to facilitate the nucleation and separate crystals from the liquid phase. The
1551 process has the advantage of allowing large phosphate salt pellets to be kept in
1552 suspension in the bottom of the reactor without washing out fine crystal nuclei
1553 from the top of the reactor.

1554 ○ Type II: sludge precipitation. The *AirPrex*® process is different from the
1555 abovementioned techniques as crystallization of **the recovered phosphate salt**
1556 **occurs directly from the digested sludge**. A major advantage is the improvement
1557 of sludge dewatering. In the process, the digested sludge is led through a
1558 cylindrical reactor, with an inner cylindrical zone mixed by air upflow and a
1559 settling zone between this inner cylinder and the outer cylinder. Internal sludge
1560 recycling allows the crystals to grow, until they reach a size at which they can
1561 escape from the recycle flow and settle (Desmidt et al., 2015). The recovered
1562 phosphate is crystallized within the wet sludge and can therefore show some
1563 organic and inorganic impurities. Washing and gentle drying of the mineral
1564 crystals improves the quality and provides a marketable fertiliser product (Ewert
1565 et al., 2014). Also the Ostara's Pearl process can be combined with the Waste
1566 Activated Sludge STRIPping process WASSTRIP (Baur, 2009). Here, the
1567 digested sludge is sent to the anaerobic reactor where P and Mg are released
1568 (stripped) by the micro-organisms as a consequence of endogenous respiration and
1569 fermentation, after which the resultant P-rich liquid is sent to the precipitation
1570 reactor.

1571 ○ Type III: downstream sludge leaching after acidification. A **wet-chemical**
1572 **extraction process** to process **digested sludge from waste water treatment**
1573 **plants**. These processes can use sludges produced in biological (EBPR) and
1574 chemical (precipitation with metal salts) waste water treatment processes,
1575 although the chemical demand varies for both types of sludges. In contrast to the
1576 processes of type II, these processes enable higher P recovery efficiencies
1577 recovery by transferring (dissolving) P fixed in the solid sludge phase into the
1578 aqueous phase.

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- In the *Seaborne*® process (or Gifhorn process), nutrients are separated from the sewage sludge using a **wet-chemical process** and processed into a marketed fertiliser containing acceptable levels of heavy metals or organic pollutants (Muller et al., 2005; Desmidt et al., 2015). In the first process step, an **acidification** of the sludge occurs by the addition of H_2SO_4 in order to dissolve the solids and to release heavy metals and nutrients. In case the sludge input material originates from a plant that uses chemical precipitation, an additional precipitation step between extraction and dewatering by addition of Na_2S has been introduced in order to avoid that Fe phosphate compounds with low plant availability are transferred to the nutrient product. The remaining solids are separated from the flow by using a centrifuge and filter system, and are then dried and directed to the sludge incineration. In the next treatment step, sulphuric digester gas is used to precipitate heavy metals from the effluent liquor. In the following process step the nutrients are recycled. Phosphate is precipitated majorly as struvite by the addition of NaOH, to obtain an alkaline pH-value, and MgO as precipitant, but significant amounts of calcium phosphates can be formed likewise. Finally, the surplus N is recovered by air stripping of ammonia. Around 90% of the nutrients (P, N) could be recovered by the Seaborne process, the P as struvite, the N for just under a third in struvite and the remainder in $(NH_4)_2SO_4$ (Günther et al., 2007).
 - The *Stuttgarter*® process relies on the same principle of wet chemical treatment but differs from the Seaborne process by the fact that it uses a **chamber-filter-press for solid-liquid separation**, and that complexation of heavy metal ions to avoid co-precipitation is achieved by dosing of citric acid (Ewert et al., 2014). Here, the recovery product is mainly struvite (ca. 95%) (Ewert et al., 2014).
 - The *Budenheim*® process the sewage sludge/water suspension is aerated with carbon dioxide under pressure of approx. 10 bar. With this treatment, carbon dioxide becomes carbonic acid in the sewage liquor, the pH decreases to a value of between 4.5 and 5.5 and a part of the phosphates bound to the sewage sludge matrix is dissolved. In the following solid/liquid separation, the sewage sludge particles are separated from the liquid phase using Ca-based coagulants. The end material recovered is dicalcium phosphate.
 - Type IV: upstream sludge hydrolysis. Instead of releasing phosphorus by acidification from digested sludge by applying chemicals, **thermal hydrolysis** at temperatures between 150-200°C could be applied on secondary sludge from waste water treatment plants applying **EBPR**. This releases P to a soluble form so that higher recovery rates can be achieved by phosphate precipitation, and also improves CH_4 production. The digested sludge firstly is thickened and then subjected to hydrolysis and digestion. Digested sludge has a very high water

1621 absorbing capacity, greatly reducing the degree of dewatering in proportion to its
1622 share. Through thermal hydrolysis in a pre-treatment step, poorly degradable
1623 substrates such as proteins and polysaccharides are modified such that micro-
1624 organisms can easily degrade them. Hence, by deploying this procedure prior to
1625 primary sedimentation, the good degradability and dewaterability rates of the
1626 sludge liquor is increased (Ewert et al., 2014). Processes include thermal
1627 hydrolysis (e.g. *Cambi*, *Eliquo Stulz (LysoGest)*, *Exelys*) or thermo-chemical
1628 hydrolysis (e.g. *Pondus*). Thermal hydrolysis of the digested sludge upstream of
1629 primary sedimentation is then followed by P recovery from the fully digested
1630 sludge (e.g. AirPrex® procedure) (Ewert et al., 2014).

1631 There are specific processes (PASCH®, P-bac (INOCRE)®) that produce **struvite from**
1632 **ashes as input material**. These products will be described in section 4.2 (ash-based
1633 products).

1634

1635 4.1.2 Precipitation from other input materials

1636 **Most** of the **techniques** that recover P in the form of phosphate salts (struvite, dicalcium
1637 phosphates, or a mixture of Ca- and Mg-salts) are developed for **municipal wastewater**
1638 (Desmidt et al., 2015). P-recovery techniques based on precipitation techniques can apply in
1639 principle to all phosphate rich liquids or slurries. Therefore, the techniques can also be
1640 applied on phosphate-rich industrial waste water (e.g. potato industry, dairy industry, type I
1641 processes) and anaerobically digested biowaste and manure fractions (mostly type I
1642 applications). Although at present only applied municipal waters, also other organic C-rich
1643 materials such as manure and sludges from the food industry could be subject to P-recovery
1644 techniques that increase the recovery efficiency (type III and IV processes).

1645

1646 4.1.3 Deliberateness of the nutrient recovery

1647 The production processes can be **specifically developed** for the P-removal through the
1648 precipitation of Ca- or Mg-phosphate from phosphate rich waste water streams (often from
1649 the food processing industry). Mostly, the P-recovery installation is **an integral part of a**
1650 **larger installation** as often pre-treatment is required (e.g. EBPR, anaerobic digestion).

1651 The P-precipitation process may provide important **benefits for the simplicity of operation**
1652 **of waste water treatment plants** and associated economic returns, even without retailing the
1653 recovered phosphate salt as a fertiliser.

1654 ○ Phosphate salt producing processes of Type II and IV may **increase the**
1655 **dewaterability** of the sludge, and thus the associated costs of sludge disposal and
1656 chemical demand associated to traditional sludge dewatering options (e.g. addition
1657 of flocculation agents, acid and alkaline, etc.). At present, operating costs for
1658 sludge dewatering usually account for as high as 25–50% of the total expenses of
1659 the whole wastewater treatment processes (Mahmoud et al., 2011). The divalent
1660 cation bridging theory states that flocculation, which is strongly linked to

1661 dewaterability, is driven by the ratio of divalent cation concentrations (Ca^{2+} ,
1662 Mg^{2+}) over monovalent cations (Na^+ , K^+ , NH_4^+ , etc.). Divalent cation creates
1663 bridges between particles whereas monovalent cations tend to deteriorate flock
1664 structures. Therefore, an improved dewaterability can be expected if the addition
1665 of magnesium divalent cations surpasses the effect of sodium hydroxide dosing.
1666 Marchi et al. (2015) indicated the importance of a proper tuning of chemical
1667 additions in order to achieve progressive dewatering.

1668 ○ Waste water treatment costs are also reduced by the lower maintenance costs due
1669 to the **avoided pipe clogging and abrasion of centrifuges**.

1670 ○ The **reduction of the P and N load of the sludge liquor** has a direct effect on the
1671 treatment capacity of the whole waste water treatment plant as well as a cost
1672 factor, since the removal of nutrients from the wastewater requires energy,
1673 chemicals and tank volume (Ewert et al., 2014).

1674 The presence of some other species present in the stream or the purposeful addition of
1675 specific chemicals may cause the (co-)formation of materials other than struvite (K-struvite,
1676 calcium hydroxyl apatite, vivianite, etc.).

1677

1678 **4.2 Ash-based products**

1679 Whether ashes as obtained after the incineration processes can be suitable for direct use as a
1680 fertilising material is dependent on (1) the elemental composition of the ashes, (2) the
1681 presence of metals and metalloids in the input materials, and (3) the availability of the plant
1682 nutrients present in the ashes.

1683

1684 4.2.1 Raw ashes and melting/sintering materials

1685 4.2.1.1 *Thermal oxidation technology*

1686 Ashes obtained from the combustion of organic materials (e.g. wood residues, poultry
1687 manure, meat and bone meal, animal bones, sewage sludge) are used directly as a
1688 multinutrient fertiliser and/or liming material in many different EU Member States. Available
1689 technologies for the incineration of such organic biomass include (van Eijk et al., 2012):

1690 • **Bubbling fluidized bed boilers (BFB)** are often preferred in small-scale applications,
1691 with fuels having low heat value and high moisture content. The bed is fluidised by
1692 means of an arrangement of nozzles at the bottom of the furnace which create turbulence
1693 that enhance the mixing of the fuel, increasing the boiler's efficiency by converting
1694 unburned C remaining to usable energy. The bed is usually formed by sand and with a
1695 small amount of fuel. Solids fluidization occurs when a gaseous stream (primary air)
1696 passes through a bed of solid particles at enough velocity (above the minimum
1697 fluidization velocity) to overcome the particles gravity force. Limestone might be added
1698 to the bed to eliminate sulphur and/or chlorine. BFB operation range is between the
1699 minimum fluidisation velocity and the entrainment velocity on which the bed particles

1700 would be dragged by the passing gas, being usually 1.2 m/s at full load. Combustion
1701 temperature is typically between 800 and 950°C, being 850°C a usual bed temperature.

1702 • **Circulating Fluidized Bed** (CFB) technology boilers are normally used in larger
1703 applications, being similar in basic concept to the BFB. CFB has enhanced flexibility
1704 over BFBs for firing multi-fuels with high moisture content and significantly higher
1705 efficiency up to 95%. CFB configuration includes solid separators that separate the
1706 entrained particles from the flue gas stream and recycles them to the lower furnace. The
1707 collected particles are returned to the furnace via the loop seal. The addition of the solid
1708 separators allows CFB technology to reach the higher values regarding efficiency and
1709 availability and provides fuel flexibility. The entrainment velocity is the limit point that
1710 defines the transition from a BFB to a CFB. The CFB operation range is fixed over that
1711 entrainment velocity. Beyond this velocity the bed material becomes entrained and the
1712 solids are distributed throughout the furnace with a gradually decreasing density from the
1713 bottom to the top of the furnace. Fluidizing velocity is higher than in a BFB and can be
1714 between 4.5-6.7 m/s.

1715 • Similar to BFB, **grate boilers** are used in units below 100 MWe and normally for
1716 industrial uses. Grate technology can burn a range of fuels wider than a BFB, but worse
1717 emissions and efficiency as BFB. Grate boiler provides very good performance burning
1718 low moisture and high alkalis content fuels. Grate can burn difficult fuels as straw, little
1719 chicken, high alkaline agro crops that are more challenging to combust using BFB/CFB
1720 due to high agglomeration tendency.

1721 • Organic residues can also be heated to temperatures between 800°C and 1500°C to
1722 achieve a transformation of solid materials through **melting** (e.g. in a rotary kiln or cupola
1723 furnace). Melting occurs in a non-oxygen limiting environment, resulting in the formation
1724 of ashes and P-slugs. Due to the addition of carbonates, soda (Na_2CO_3) and quartz sand, it
1725 is possible to separate P from many other elements and to influence the crystal structure
1726 of the P containing slags (e.g. isomorphic substitution of PO_4^{3-} ionic group by SiO_2^{2-} or
1727 CO_3^{2-}) affecting the reactivity of the final product and therefore the plant P availability.
1728 Metals/metalloids are partially volatilised (Zn, Cg, Hg, F), partially remain in the metal
1729 fraction (e.g. Fe, Cu, Cr, Ni) or remain in the slags (see post-processing). Therefore, this
1730 process can be applied on non-combusted organic materials or as a post-processing step
1731 on incineration ashes to improve the material quality (see section 4.2.1).

1732
1733 **Also steelmaking** processes make use thermal oxidation melting processes in blast furnaces
1734 and electric arc furnace. Steel slag is produced as molten rock at around 1650°C during the
1735 conversion of hot metal, sponge iron or steel scrap into crude steel. It consists of the oxidised
1736 accessory elements from hot metal, steel scrap and the other metallic substances, and of the
1737 slag-forming additives such as limestone, burnt lime or dolomite. Depending on how the
1738 crude steel is produced, a distinction is made between basic oxygen furnace slag from the
1739 basic oxygen furnace process, and electric arc furnace slag from the electric arc furnace
1740 process. A **blast furnace** is a type of metallurgical furnace that relies on thermal oxidation
1741 for smelting to produce industrial metals. In a blast furnace, fuel, ores, and flux (limestone)
1742 are continuously supplied through the top of the furnace, while a hot blast of air (sometimes

1743 with oxygen enrichment) is blown into the lower section of the furnace through a series of
1744 pipes called tuyeres, so that the chemical reactions take place throughout the furnace as the
1745 material moves downward. An **electric arc furnace** is a furnace that heats charged material
1746 by means of an electric arc. Modern furnaces mount, however, oxygen-fuel burners in the
1747 sidewall and use them to provide chemical energy to the cold-spots, making the heating of the
1748 steel more uniform. Additional chemical energy is provided by injecting oxygen and carbon
1749 into the furnace. In specific metallurgic treatments under development (Bartsch et al., 2014),
1750 organic residues or their ashes are heated together with mineral ores to achieve a
1751 reconfiguration of the solid materials with the intention to improve the quality (e.g. increased
1752 plant availability through the formation of silicophosphates, reduced metal content) of the
1753 resulting P-rich fertilising material (see section 4.2.2).

1754

1755 *4.2.1.2 Flue-gas treatment systems*

1756 Flue-gas treatment (FGT) systems are constructed from a combination of individual process
1757 units that together provide an overall treatment system for the flue-gases (European
1758 Commission, 2006a). The individual components of a FGT system are combined to provide
1759 **an effective overall system for the treatment of the pollutants that are found in the flue-**
1760 **gases.** There are many individual components and designs, and they may be combined in
1761 many ways. The diagram below shows an example of the options and their possible
1762 combination (European Commission, 2006a). The FGT technology impacts upon the quality
1763 of the combustion residues.

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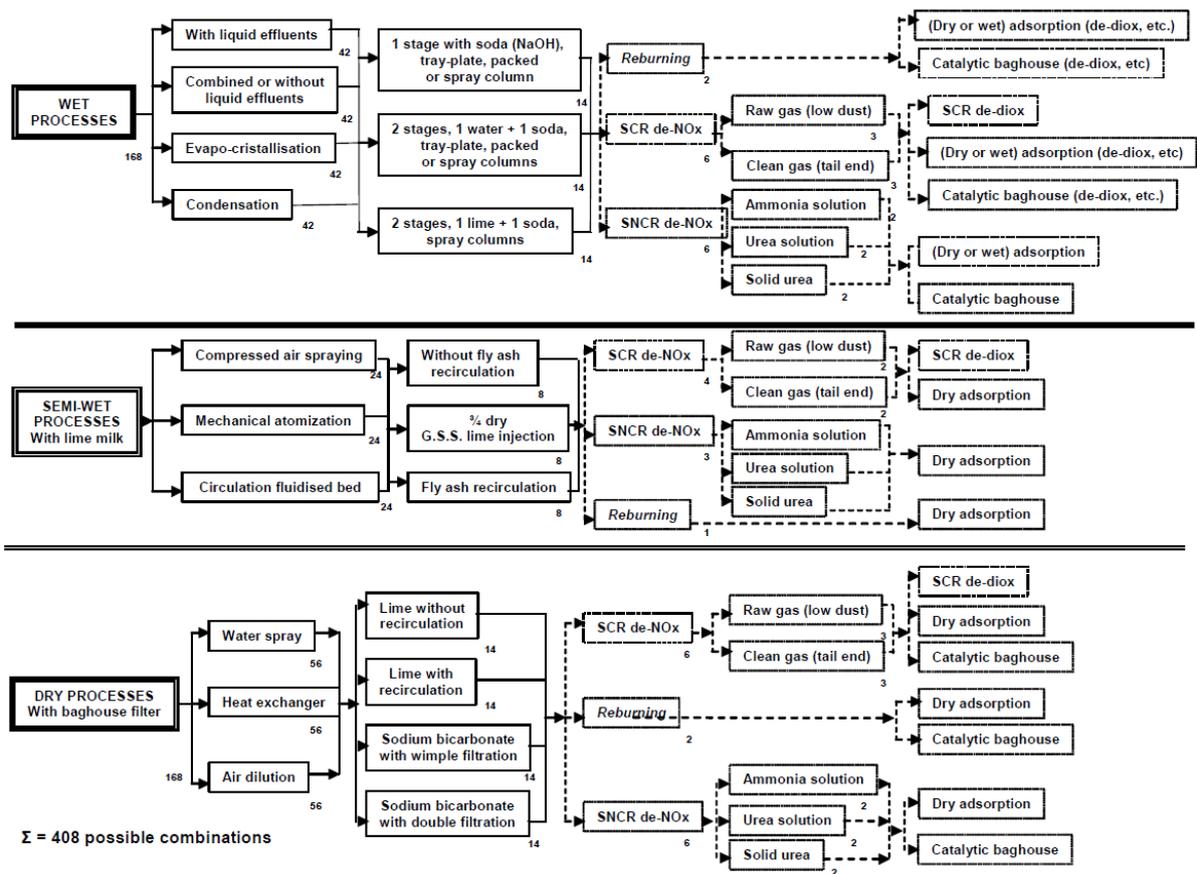


Figure 6: Overview of potential combinations of fluegas treatment systems (European Commission, 2006a)

4.2.2 Ash derivatives

The use of **raw ashes** in agriculture can be associated to two major issues (Chandrajith and Dissanayake, 2009; Herzel et al., 2016). At first, the conditions during incineration induce a wide range of structural modifications that **reduce the P-solubility and plant availability**. Secondly, ashes produced of specific input materials (e.g. sewage sludge) contain **high contents of metals/metalloids**. Hence, direct fertiliser use will return these potentially toxic elements into soil, water, air, food crops, and ultimately the human body tissues via the food chain.

Ashes not suitable for direct recycling can be treated through two different routes that aim at P-recovery: (1) wet-chemical processes and (2) thermal processes (Table 8). Ashes from mono-incineration (i.e. not mixed with low-P wastes like industrial sludges, municipal solid refuse) are relevant for enhanced P-recovery strategies because of the high P content. These processes are especially relevant for P-rich ashes generated from sewage sludge, meat and bone meal, manure, etc. Phosphorus **recovery rates** from mono-incinerated ashes can reach **up to 90%** (Cornel and Schaum, 2009). For sewage sludge ashes, specific thermal as well as wet-chemical processes are able to process **ashes originating from EBPR as ChemP plants** (Kabbe et al., 2015).

- 1786 • Type I: wet-chemical processes
- 1787 ○ An almost complete **acidic dissolution of P at pH-values below 2** through the
- 1788 addition of chemicals is the principle of action to recover P via wet-chemical
- 1789 extraction techniques. This process is unavoidably accompanied by a partial
- 1790 dissolution of metals or their compounds. The amount of dissolved metals
- 1791 depends on the composition of the raw input material (Fe- or Al-rich) as well as
- 1792 on the type and amount of the added acid (H₂SO₄ or HCl). Thus, after acidic
- 1793 leaching the toxic inorganic contaminants (e.g. Pb, Cd, Hg, etc.) have to be
- 1794 separated from the dissolved P in order to create a valuable P-recovery product.
- 1795 Additionally, it is desirable to separate especially Al and Fe as well, as these
- 1796 elements impair the quality of the recovery product. **For the removal of cations**
- 1797 **from the acidic leachate** different approaches are technically feasible to obtain
- 1798 satisfactory P-removal: sequential precipitation, liquid-liquid extraction, and ion
- 1799 exchange (Table 8).
- 1800 ■ P-rich ashes of specific characteristics can replace ground phosphate rock
- 1801 in the **acidulation process applied by the fertiliser industry**. The
- 1802 addition of sulphuric acid or nitric acid will result in the production of
- 1803 phosphoric acid that can then be used for the production of traditional P-
- 1804 fertilisers (e.g. DAP, MAP, TSP, nitrophosphate, etc.). The P-rich ashes
- 1805 should be consistent and the Fe/Al content should be relatively low in
- 1806 order to enable the partial substitution of phosphate rock by ashes in the
- 1807 process (Langeveld and Ten Wolde, 2013).
- 1808 ■ The basis of the **SEPHOS process** is the **sequential precipitation** of P
- 1809 complexes with an alkaline treatment (Takahashi et al., 2001; Schaum,
- 1810 2007). The separation of dissolved P from heavy metals is achieved by
- 1811 raising the pH-value in the acidic leachate to induce the precipitation of
- 1812 Al-P while most heavy metals remain in solution (Takahashi et al., 2001).
- 1813 The heavy metal content of the Al-P product is then further decreased by
- 1814 precipitating heavy metals with sulphide (Schaum, 2007). Since the entire
- 1815 P has to be precipitated as Al-P, this process is especially suitable for Al-
- 1816 rich ashes coming from waste water treatment plants that employ chemical
- 1817 P-removal by addition of Al-salts. Since Al-P cannot be directly reused as
- 1818 fertiliser, the precipitated Al-P may be dissolved by alkaline treatment
- 1819 followed by precipitation as Ca-P. Altogether, this type of wet chemical P-
- 1820 recovery process results in a total chemical demand (at least 600 g H₂SO₄
- 1821 /kg ash and 300 g NaOH/kg ash) (Schaum, 2007). A P-recovery rate of
- 1822 90% is documented for the Sephos process. The **SESAL-Phos process**
- 1823 (Petzet et al., 2012) applies a softer acidification treatment (to a pH value
- 1824 of around 3 through HCl addition), followed by direct alkaline dissolution
- 1825 of P. In this case, only the low amounts of P dissolve, while most (heavy)
- 1826 metals remain in the ash. In a following process step, the dissolved P can
- 1827 be precipitated from the alkaline solution (pH > 13) as Ca-P with a very
- 1828 low impurity level, via the addition CaCl₂. The amount of Al-P directly

1829 leachable via alkaline treatment depends on both the Al content and the Ca
1830 content of the ashes (Schaum, 2007). In case of sewage sludge ash with
1831 very low Ca contents, a significant amount of P can be dissolved with low
1832 chemical demand, for which the process is more suitable for soft waters.
1833 Consequently, the SESAL-Phos process leads to a significantly reduced
1834 specific chemical demand, but the recovery rate of 74-78% is lower for the
1835 SEPHOS process (Petzet et al., 2012).

1836 The **Leachphos®** process is another **sequential process** with a leaching
1837 and a precipitation step to treat fly ash, amongst other from municipal
1838 solid waste incineration (Adam et al., 2015). The first step is leaching of
1839 sewage sludge ash with dilute H₂SO₄ that dissolves about 70-90 % of the P
1840 in the ashes, depending on acid concentration and reaction time. The
1841 leaching is followed by a solid/liquid separation step carried out on a
1842 vacuum belt filter or in a filter press. The leached sewage sludge ash filter
1843 cake is withdrawn from the process and must be disposed. The P
1844 containing liquid is pumped into a second stirred reactor, where dissolved
1845 P is precipitated by dosing of lime (CaO) or caustic soda (NaOH). A
1846 product with relatively high P content (13% P), considerable metal
1847 depletion and sufficient dewaterability is thereby produced (Adam et al.,
1848 2015). Depending on the precipitation agent, P is present in different
1849 mineral phases. If precipitated mainly with lime, P is present in the form of
1850 **calcium phosphate next to aluminium phosphate**. After precipitation
1851 and separation of the phosphorus product, the liquid waste stream requires
1852 additional treatment. Treatment consists of pH elevation to a pH of 9 by
1853 dosing of additional lime and of sulphidic precipitation of metals by an
1854 organosulphide precipitation agent (Adam et al., 2015). This is carried out
1855 in a third reactor followed by an additional solid/liquid separation step by a
1856 filter press. Thus the metals in the wastewater are removed almost
1857 completely. Thereafter, the pH in the waste water is adjusted to a pH of 7
1858 and is discharged either to a waste water treatment plant or directly to a
1859 receiving water body (Adam et al., 2015).

1860 ■ The **PASCH®** (Phosphorus recovery from Ash, developed at Aachen
1861 University) process utilizes **liquid-liquid extraction** for heavy metal and
1862 iron separation (Nieminen, 2010; Pinnekamp et al., 2010). Different acids
1863 were tested for P-dissolution by Montag and Pinnekamp (2009) with
1864 results of 25%, 50%, 80% and 90%, for NaOH, H₃PO₃, H₂SO₄ and HCl
1865 respectively. After the acid leaching, a lamella separator and filter separate
1866 the residue. The filtrate, containing phosphorus, calcium, and metal
1867 compounds, is treated in the extraction step with Alamine 336 and
1868 tributylphosphate (TBP). Reduction in the heavy metal concentrations is
1869 over 95% and iron over 99%. The final step precipitates the phosphate as
1870 calcium phosphate or struvite depending on precipitation chemical (i.e.
1871 lime or magnesium compounds).

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- The **BioCon® process** recovers P as H_3PO_4 from sewage sludge ashes (Balmér et al., 2002; Nieminen, 2010). The entire process consists of three phases: sludge drying, sludge incineration, and recovery unit with **ion exchangers**. The first step of the recovery process dissolves the P and heavy metal contents with H_2SO_4 at a pH value of 1 (Berg and Schaum, 2005; Herrman, 2009). The solution passes through a series of ion exchangers. The first exchanger is cationic, separating Fe^{3+} ions. It is regenerated with HCl producing $FeCl_3$. The following exchanger is anionic, collecting K^+ ions, and after regeneration with H_2SO_4 produces $KHSO_4$. In this step, NaOH is used for both pH adjustment and regeneration (Hultman et al., 2001). The final exchanger collects phosphates. Regeneration with HCl produces a stream of H_3PO_4 (Lundin et al., 2004). It should be emphasized that H_3PO_4 has no soil fertilising properties on its own; it is an intermediate in the production process of mineral P-fertilisers.
 - Additionally, there are different patented multi-modular approaches of which the process detail are kept confidential. The **EcoPhos® process** is already implemented at full-scale and relies on a multi-step approach to valorise low grade phosphate rock and also P-rich ashes to high quality market products as H_3PO_4 or dicalcium phosphate (DCP) (EcoPhos, 2016). First step is the leaching of the ash with HCl. Undergoing different modules (including ion exchange resins) which are kept confidential, a purified H_3PO_4 for fertiliser or food and feed industry is produced. At the same time most of the produced residues are sellable products as $CaCl_2$, gypsum, silicate as well as iron- and aluminum chlorides. With the **TetraPhos® process**, Remondis developed and implemented a similar approach in pilot scale (Hamburg) using H_3PO_4 instead of HCl to the leach the ash, and ending up with H_3PO_4 as a final product (Remondis Aqua, 2016). Also in the acid leaching **RecoPhos® process** (Weigand et al., 2013; RecoPhos, 2016), the plant-available phosphate fraction is increased by reacting the sewage sludge ash with H_3PO_4 . Thereby, the primary minerals are transformed into soluble calcium and magnesium dihydrogen phosphate, the primary nutrient components of the RecoPhos P 38 fertiliser. The piloting **Edask process** relies on semi-permeable membranes, under the influence of an electric potential, to separate phosphate ions (electrodialysis) (Thornberg, 2015). The P-recovery end product is H_3PO_4 .
 - The **P-bac process®** offers selective recovery of P from sludge ash, bed ash and contaminated soils via a biotechnological route (Inocre Biotech, 2016). The P-bac process combines efficient and selective phosphate recovery with **bioleaching** and therefore is especially suitable for solids with high content of heavy metals. The selective recovery of phosphate with the P-bac process is realised in two phases. The first step is based on the “bioleaching principle”, which is applied worldwide

1915 for the exploitation of metals (e.g. Cu, Zn, U, etc.) in the mining industry. By
1916 **microbial generation of H₂SO₄**, phosphate derivatives and metals/metalloids are
1917 dissolved within few hours. The remaining solid matter is separated from the
1918 liquid matter and can be disposed for reduced costs. The phosphate-enriched
1919 biomass subsequently is separated from the liquid phase and can be precipitated as
1920 struvite after anaerobic dissolution. Up to 90% of the original phosphate can be
1921 recovered with the P-bac process.

1922 • Type II: Thermal processes

1923 ○ Nutrients can be recovered from ashes by high temperature treatments (Table 8).
1924 Processes were developed that transfer P into a metallurgical slag by reductive
1925 smelting at very high temperature temperatures in a shaft furnace (Scheidig, 2009)
1926 or that reduce P to elemental P that is separated via the gas phase in an inductively
1927 heated shaft furnace (Schönberg et al., 2014). The general principle is that volatile
1928 heavy metals such as Zn, Pb, Cd and Hg are separated from the product via the
1929 gas phase and further collected in the flue dust, and heavy metals with high
1930 boiling points such as Fe, Cu, Ni and Cr are separated in the form of a liquid alloy.

1931 ■ The **Mephrec** (Metallurgical Phosphorus Recovery) process was
1932 developed by the German company Ingitec. The process recovers P and
1933 energy from sludge and many other input materials of high calorific value
1934 such as meat and bone meal and/or wood ash. **Dried sludge** is briquetted
1935 with slag forming substances and coke. The mixture is treated in 2000°C
1936 transferring P into the mineral slag and heavy metals to liquid metal phase
1937 (Fe, Cu, Cr, Ni) or to gaseous phase (Hg, Cd, Pb, Zn). The silico
1938 phosphates containing slag is separated from metal phase after being
1939 tapped at 1450°C (Adam 2009). The final product contains, depending on
1940 the input materials used, 5-10% P with over 90% citric acid solubility. The
1941 P content can be varied by mixing sewage sludge with animal meal. The
1942 energy recovery from high-calorific raw off-gas can be realized either by
1943 directly combusting and using the heat in an Organic Rankine Cycle
1944 (ORC) process, or multi-stage gas cleaning and use in a combined heat and
1945 power (CHP) plant (Adam et al., 2015). With **sewage sludge ash**, the P
1946 content can reach up to 9%, but energy recovery is not possible.

1947 ■ The **FEhS/Salzgitter process** is a process to increase the P-content of
1948 liquid steel slag with phosphorus by blending it with ashes from the
1949 incineration of P-containing materials like sewage sludge and/or meat and
1950 bone meal. For the process, the slag is separated from the metal bath and
1951 transferred to an external slag pot, in which the cold ash is blown into the
1952 melt from the top together with oxygen or air. In the liquid slag the ash's
1953 phosphates are dissolved. After cooling and solidification, P₂O₅ is
1954 converted to plant-available Ca-Si-phosphate, similar to the phosphate in
1955 Thomas ground basic slag. The oxidation of residual metallic iron and
1956 bivalent iron in the steel slag produces the energy to maintain the

1957 necessary process temperatures of around 1500°C. The process has been
 1958 tested in laboratory and in industrial scale.

1959 ▪ The melting process of the Japanese company **Kubota** has been developed
 1960 for municipal solid waste, sewage sludge, landfill waste and ashes thereof.
 1961 It enables the separation of P-slag through a temperature treatment of
 1962 1250~1350°C. P is immobilized in the slag (~13% P) with a recovery rate
 1963 of > 80% (Kubota, 2015).

1964 ○ The **ASH DEC** process (OutoTec) treats mono-incinerated sewage sludge ashes
 1965 by a **sodium sulphate dosage and thermal treatment** below the melting point of
 1966 sewage sludge ash in order to remove heavy metals making the product suitable
 1967 for agricultural use by increasing the plant availability of P. An ASH DEC plant
 1968 could stand alone and being operated as greenfield facility. For economic and
 1969 ecological reasons it is planned to **combine the ASH DEC plant with mono-**
 1970 **incineration**. The main advantage of the combination is the possibility of feeding
 1971 hot ash directly from the mono-incineration plant to the ASH DEC facility, thus
 1972 saving energy and equipment (Adam et al., 2015). In the first step, the ash is
 1973 mixed with Na₂SO₄ in the thermally treated ash. Fresh Na₂SO₄ input could be
 1974 partly replaced by recycled Na₂SO₄ from the mono-incineration. Alternatively
 1975 (older process), MgCl₂ can be used for higher removal rates of heavy metals in the
 1976 process, but this pathway results in reduced plant availability of the recovered
 1977 phosphates. The dried sewage sludge (> 80 % dry matter) is charged in granules
 1978 and is used as reducing agent in the ASH DEC process for the reduction of
 1979 sulphate in the Na₂SO₄ and metal compounds. The thermal reaction is performed
 1980 in a directly heated rotary kiln in counter flow having maximum temperatures of
 1981 900-950°C. At this temperature, metals/metalloids react with the salts, become
 1982 gaseous, and evaporate. After cooling, the P-rich ashes (P content of about 5-10%)
 1983 are in the form of small granules and may be finished on site or in cooperation
 1984 with a customer at the site to further increase agronomic values.

1985 ○ The **EuPhoRe®-Process** begins with application of additives into the dewatered
 1986 or dried sewage sludge. The following energy utilisation is characterised by
 1987 volatile components degassing during a reduction period under application of
 1988 medium temperature pyrolysis at 650 to 750 °C and is linked to an immediate
 1989 subsequent post-combustion of the remaining fixed carbon at temperatures
 1990 between 900 and 1.100 °C. During the first reductive process step, the heavy
 1991 metal compounds contained in the sewage sludge are already partly transformed
 1992 into the gas phase, although it is continued throughout the oxidative second
 1993 process step, the carbon post-combustion. The metal compounds are being
 1994 efficiency released and significantly improved through additive compounds of
 1995 alkaline and/or earth alkali salts, such as MgCl₂. Magnesium remains into the
 1996 phosphate-fertiliser and improves the plant availability. Chlorides take the reduced
 1997 heavy metals into the gas stream. The generated phosphate fertiliser contains low-
 1998 carbon (2 – 6% C) and the heavy metal compounds are partly to a vast extent

1999 depleted (up to > 98%). The fertiliser contains nearly the entire phosphate load of
2000 the input material and after grinding as well as dust collection consequently allows
2001 for a direct agricultural utilisation. The energy content of dewatered sewage
2002 sludge (>25% dried matter) is sufficient for a complete thermic, self-sustaining
2003 production facility operation including the required drying process.

2004 ○ The **thermo-reductive RecoPhos** is a thermo-chemical process involving the
2005 fractioned extraction of P and heavy metals from sewage sludge, meat and bone
2006 meal and sewage sludge ashes at high temperatures under reducing conditions
2007 (Steppich, 2015). Thermal process uses **electro-magnetically induced heating** of
2008 a reactor bed consisting of coke or graphite. The induction heating systems serve
2009 alternating magnetic fields with high energy density and thus provide the reaction
2010 conditions required for the molten ash to react with the C. The reductive processes
2011 taking place within the reactor are based on the Woehler reaction at a temperature
2012 of 1200-1400°C, which is the same chemical principle as the one used in the well-
2013 established submerged arc furnace, producing high grade elemental P as vapour,
2014 which can be either condensed and harvested as P₄ or subsequently oxidised to
2015 P₂O₅ or converted into H₃PO₄. The process enables the use of waste materials as
2016 heat sources, reducing agents or additives, including dried sewage sludge, foundry
2017 ash, waste salts or meat and bone meal, and low grade phosphate rock, with as
2018 advantage that in the RecoPhos process no pre-agglomeration of powder feedstock
2019 is needed and no dioxin emissions takes place. The Recophos process also claims
2020 to be able to recover P from raw materials containing significant levels of Fe from
2021 ChemP waste water treatment plants. The end product P₄ can then be used for
2022 production of flame retardants or lubrication additives while H₃PO₄ can then be
2023 further used for the production of inorganic P-fertilisers and other P-containing
2024 products. The thermo-reductive RecoPhos technology has been acquired by **ICL**
2025 (Israel Chemicals Ltd) for the industrial scale production of P-fertilisers derived
2026 from secondary raw materials.

Table 8: Overview of the principles and properties of P-recovery processes from ashes.

process name	status	route	P-separation	products	P-recovery	ref.
SEPHOS	unknown	wet-chemical	sequential precipitation (strong acid, alkalines)	calcium phosphates	90%	(a)
SESAL-Phos	piloting at laboratory scale	wet-chemical	sequential precipitation (mild acid, alkalines)	calcium phosphates	74-78%	(b)
LeachPhos	piloting/planned	wet-chemical	sequential precipitation (strong acid, alkalines)	calcium phosphate, aluminium phosphate	70-90%	(c)
PASCH	unknown	wet-chemical	liquid-liquid extraction	calcium phosphate, struvite	90%	(d)
BioCon	unknown	wet-chemical	ion exchange	H ₃ PO ₄	60%	(e)
EcoPhos	piloting/constructing/operating	wet-chemical	confidential, including ion exchange	H ₃ PO ₄ , dicalciumphosphate	97%	(f)
TetraPhos	piloting	wet-chemical	confidential	H ₃ PO ₄	unknown	(g)
RecoPhos (P 38)	operating	wet-chemical	confidential	mostly calcium and magnesium phosphates	98%	(h)
Edask	piloting	wet-chemical	ion exchange (electrodialysis)	H ₃ PO ₄	unkown	(i)
P-bac	piloting	wet-chemical	bioleaching	struvite	90%	(j)
Mehprec	piloting/constructing/planned	thermal	not applicable	P-rich slag (5-10% P)	80%	(k)
Kubota	operating (Japan)	thermal	not applicable	P-rich slag (~13% P)	> 80%	(l)
Ash Dec	piloting/planned	thermal	not applicable	P-rich ashes (5-10% P)	98%	(m)
RecoPhos (ICL)	piloting/planned	thermal	not applicable	elemental P, P ₂ O ₅ and H ₃ PO ₄	89%	(n)

(a) Schaum et al., 2005; Schaum, 2007, (b) Petzet et al., 2012, (c) Adam et al., 2015, (d) Pinnekamp et al., 2010, (e) Balmer et al, 2002,

(f) Adam et al., 2015; EcoPhos, 2016, (g) Remondis Aqua, 2016, (h) Weigand et al., 2013, RecoPhos, 2016, (i) Thornberg, 2015,

(j) Inocre Biotech, 2016, (k) Adam et al., 2015, (l) Kubota, 2015, (m) Adam et al., 2015, (n) Steppich, 2015

2029 4.2.3 Deliberateness of the nutrient recovery

2030 Thermal oxidation processes may be performed for sanitisation and volume reduction of
2031 waste-based materials. Also synergies with energy recovery is possible for organic materials,
2032 but the energy recovery potential in mono-incineration plants is largely dependent on the
2033 moisture content of the input materials. The chemical or thermal post-processing described
2034 above are mainly designed with the **specific aim of P recovery and/or to improve material**
2035 **properties**, and rely on the input of ashes from **mono-incineration facilities**. Finally, P-slags
2036 from the steel industry are produced as a residue from the steelmaking industry.

2037 Ashes produced through **co-incineration** (incineration together with municipal solid waste or
2038 industrial waste) typically have lower P contents that pose **increasing difficulties for**
2039 **nutrient recovery using current techniques**. Such plants are targeted towards energy
2040 recovery and carbon abatement. The Mehprec and Ash Dec processes are currently the only
2041 pathways that integrate nutrient and energy recovery when treating sewage sludge material.
2042 Kalmykova and Fedje (2013) performed a pilot using **ashes with a low P-content**
2043 **originating from municipal solid waste incineration** using acidic leaching/precipitation
2044 and acidic/alkaline leaching. The processes indicated low P-recovery potentials due to the
2045 high Ca content of the ash (acidic/alkaline leaching method), meanwhile also the trace metal
2046 content of the obtained end product could limit the direct application of this product on
2047 agricultural land (acidic leaching/precipitation method).

2048

2049 4.3 Pyrolysis materials

2050 4.3.1 Pyrolysis spectrum production techniques

2051 Pyrolysis spectrum techniques take place in an oxygen-deficit environment or with a
2052 controlled amount of oxygen and/or steam that limit the chemical reactions that transform
2053 input materials into chars. The extent to which pyrolysis materials burn depends on the ratio
2054 between the number of moles of oxygen admitted in the reactor and the moles of oxygen
2055 required for complete combustion. The less oxygen present in the reactor, the more solid
2056 pyrolysis material is produced. There are several available thermochemical technologies that
2057 operate in an oxygen-limited environment:

2058 • **Hydrothermal carbonisation** involves treatment in a closed system at moderate
2059 temperatures (~ 180°C - 300°C) and a pressure of approximately 10 bar over an
2060 aqueous solution of biomass for several hours, resulting in the production of char-type
2061 like materials as residues.

2062 • **The pyrolysis** process produces three different products that depend on the
2063 technology used, namely **biochar** (solid), **syngas** (non-condensable gases), and **bio-**
2064 **oil** (condensable liquid residue). The thermochemical decomposition of the organic
2065 materials takes place by heating in an oxygen-deficient environment at moderate to
2066 high temperatures (~ 300°C - 700°C). Pyrolysis systems use kilns or retorts, and
2067 exclude oxygen while allowing the pyrolysis gases, or “syngas” to escape and be
2068 captured for combustion.

2069 • **Gasification** is a process that converts organic feedstocks into carbon monoxide,
2070 hydrogen and carbon dioxide. The material is treated at high temperatures ($> 700^{\circ}\text{C}$),
2071 with a controlled amount of oxygen and/or steam. Gasification generally produces
2072 less solid materials compared to pyrolysis, because some oxygen is intentionally
2073 introduced in the system.

2074 For simplicity, pyrolysis materials will refer to all three techniques as the critical factor for
2075 this CMC is that the chemical reactions that transform input materials are limited by the
2076 amount of oxygen and/or steam.

2077
2078 There are a number of different reactor configurations that can achieve this including ablative
2079 systems, fluidised beds, stirred or moving beds and vacuum pyrolysis systems. For a more
2080 detailed description, it is referred to Venderbosch and Prins (2010).

2081
2082 Pyrolysis can be an **endothermic or exothermic reaction** depending on the reactor
2083 temperature and the moisture content of the input materials, becoming increasingly
2084 exothermic as the reaction temperature decreases (Mok and Antal, 1983). The exothermicity
2085 of the slow pyrolysis reaction per unit of biochar yield is reported to range from 2.0 to 3.2 kJ
2086 g^{-1} biochar (Mok and Antal, 1983; Milosavljevic et al., 1996).

2087
2088 4.3.2 Spectrum of pyrolysis materials

2089 Materials produced by pyrolysis spectrum techniques largely reflect the elemental
2090 composition of the input material that was used for the process. The **organic carbon content**
2091 **of pyrolysed chars fluctuates between 5% and 95%** of the dry mass, dependent on the
2092 feedstock and process temperature used. Some pyrolysis materials made of plant-based
2093 materials often have a high organic C content, but low nutrient content. An important
2094 defining feature of these materials is a certain level of organic C forms, called fused aromatic
2095 ring structures that relate to many of the soil improving properties ascribed to the material.
2096 Such materials are typically defined as biochar, and have organic C contents $> 50\%$. Mineral-
2097 rich input materials such as manure, and feedstock containing large amounts of animal bones,
2098 are much lower in organic C. Therefore, the European Biochar Certificate refers to pyrolysed
2099 organic matter with a C content lower than 50% as pyrogenic carbonaceous materials, instead
2100 of biochar. In the STRUBIAS framework, the name pyrolysis materials has been proposed as
2101 a common name for all material produced in an oxygen-limiting environment, although a
2102 distinction has been made between C-rich (e.g. woody biomass) and nutrient-rich pyrolysis
2103 materials.

2104
2105 4.3.3 Deliberateness of the nutrient recovery

2106 Pyrolysis processes are mostly performed with the specific aim of producing a high-value
2107 product with a set of specific properties that relate to its function (e.g. soil improver, P-
2108 fertiliser). Pyrolysis can also be performed in order to enable a volume reduction of the input
2109 materials, facilitating its further handling, transport, and distribution. Also synergies with

2110 energy recovery is possible for organic materials, but the energy recovery potential in mono-
2111 incineration plants is largely dependent on the moisture content of the input materials.

2112 Pyrolysis materials can also be produced for objectives other than nutrient recovery. Biochar
2113 application to soil is described as a **climate change mitigation strategy** (Woolf et al., 2010).
2114 The transformation of labile to recalcitrant C compounds in the biochar production process
2115 has been suggested as a means of abating climate change. Apart from its application to the
2116 soil, **biochar can also be used for other applications** (Schmidt and Wilson, 2016):

- 2117 ○ The cascaded use of biochar in animal farming (silage agent, slurry treatment,
2118 feed additive);
- 2119 ○ Use as a soil conditioner (carbon fertiliser, compost, plant protection);
- 2120 ○ Use in the building sector (insulation, air decontamination, humidity regulation);
- 2121 ○ The treatment of waste water (active carbon filter, pre-rinsing additive);
- 2122 ○ The treatment of drinking water (micro filters);
- 2123 ○ Other uses (exhaust filters, carbon fibers, semiconductors, etc.).

2124

2125

2126

DRAFT - WORK IN PROGRESS

2127 5 Agronomic efficiency

2128 5.1 Introduction

2129 Knowledge of the agronomic efficiency of STRUBIAS materials is the key starting point in
2130 any assessment of the following impacts:

- 2131 • environment & human health impacts: the relative amount of STRUBIAS fertilisers
2132 needed to achieve the same agronomic objectives as with an alternative fertilising
2133 material will determine what will be the relative impact on the environment and
2134 human health from the production and use phases of any substituting STRUBIAS
2135 fertilisers;
- 2136 • market impact: the price setting and development of the market share of any
2137 STRUBIAS materials will depend on what agronomic value they provide to the user,
2138 compared to alternative fertilising materials on the market.

2139
2140 In this section, the agronomic value of fertilising products containing recovered materials was
2141 evaluated for **different soils and plant types prevalent in the European context**. For this
2142 purpose, meta-analyses were performed that assessed the **fertiliser efficiency** of fertilisers
2143 derived from STRUBIAS materials. The term meta-analysis refers to **a statistical analysis of**
2144 **combined data from a series of well-conducted primary studies, in order to obtain a**
2145 **more precise estimate that reduces the size of the confidence interval of the underlying**
2146 **“true effect” in comparison to any individual study** (Pogue and Yusuf, 1998; Garg et al.,
2147 2008). Meta-analysis techniques enable establishing whether the scientific findings are
2148 **consistent and generalisable** across settings and facilitate understanding the reasons why
2149 some studies differ in their results. For these reasons, a meta-analysis of similar, well-
2150 conducted, randomized, controlled trials has been considered one of the highest levels of
2151 evidence (Garg et al., 2008).

2152 2153 5.2 P-fertilisers containing STRUBIAS materials

2154 5.2.1 Meta-analysis approach

2155 In the proposal for the Revised EU Fertiliser Regulation, **mined and synthetic inorganic**
2156 **fertilisers are considered in the PFC 1**. The overall share of these materials is included in
2157 the category "Straight solid inorganic macronutrient fertiliser" and "Compound solid
2158 inorganic macronutrient fertiliser". A P_2O_5 lower limit value of 12% is considered for the first
2159 category, whereas the second category requires a minimum P_2O_5 content of 3% P_2O_5 plus the
2160 presence of one of the other considered plant macronutrients (K_2O , MgO , N , CaO , SO_3 , or
2161 Na_2O). Solid organic (> 15% organic C) and organo-mineral (> 7.5% organic C) P-fertilisers
2162 require a minimum P_2O_5 content of 2% (0.9% P). Therefore, **this assessment focuses on**
2163 **STRUBIAS materials that have a minimum P_2O_5 content of > 2%**.

2164
2165 The agronomic efficiency of fertilisers was assessed using two different **plant response**
2166 **variables** (Figure 7):

- 2167 i. **The plant dry matter yield (DMY)**: This is the most common response parameter
2168 documented in studies. Comparing the absolute values for DMY from F_{prim} and F_{sec}

2169 (referring to P fertilisers derived from primary and secondary raw materials,
2170 respectively), provides precise information on the different plant biomass responses in
2171 function of the fertiliser type.

2172 ii. **The phosphorus use efficiency (PUE):** Plant P uptake efficiency is calculated as the
2173 difference in P uptake between fertilised (PU_F) and unfertilised plants (PU_C),
2174 expressed relative to the amount of fertiliser P applied (P_{applied}):
2175

$$2176 \quad PUE = (PU_F - PU_C) / P_{\text{applied}} = \Delta PU / P_{\text{applied}}$$

2177
2178 This parameter takes into account that the consumer valuation of P-fertilisers equals
2179 the marginal yield increase relative to an unfertilised treatment. The disadvantage of
2180 this parameter is, however, a higher degree of uncertainty due to error propagation
2181 because unfertilised treatments have to be subtracted during parameter calculation.
2182 Therefore, only results of studies that documented a significant increase in plant
2183 uptake relative to control for P-fertilisers derived from phosphate rock were taken into
2184 consideration (see box 1).
2185

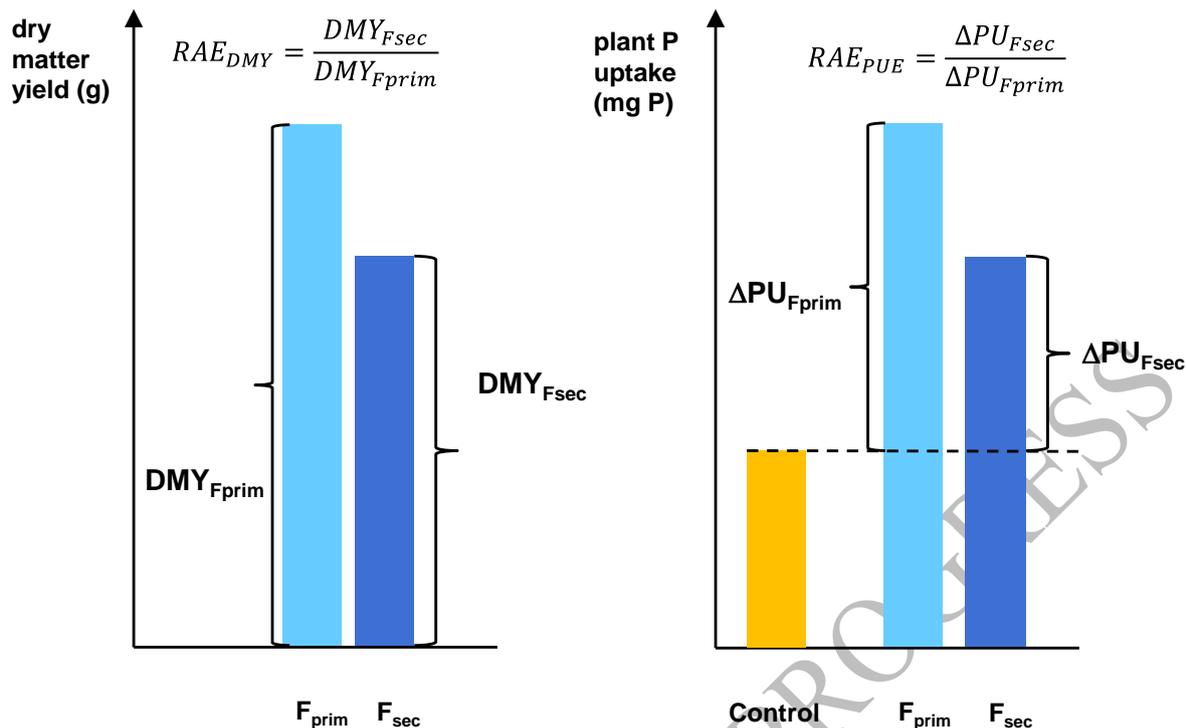
2186 This study compares plant responses to P fertilisers derived from primary and secondary raw
2187 materials (F_{prim} and F_{sec}). For F_{sec} , an assessment has been made for each of the three
2188 STRUBIAS materials. The agronomic efficiency of fertilisers containing STRUBIAS
2189 materials is expressed relative to mineral P-fertilisers; the resulting ratio is referred to as
2190 "**relative agronomic efficiency (RAE)**" (Figure 7):
2191

$$2192 \quad RAE_{\text{DMY}} = \text{DMY}_{F_{\text{sec}}} / \text{DMY}_{F_{\text{prim}}}$$

2193
2194 and
2195

$$2196 \quad RAE_{\text{PUE}} = PUE_{F_{\text{sec}}} / PUE_{F_{\text{prim}}} = \Delta PU_{F_{\text{sec}}} / \Delta PU_{F_{\text{prim}}}$$

2197
2198 Note that the P application rate (P_{applied}) is levelled by dividing $PUE_{F_{\text{sec}}}$ by $PUE_{F_{\text{prim}}}$ to
2199 calculate RAE_{PUE} .
2200
2201



2202
2203
2204
2205
2206
2207

Figure 7: Schematic outline of the plant response variables used to calculate the relative agronomic efficiencies RAE_{DMY} and RAE_{PUE} , following treatment with fertilisers from primary materials (F_{prim}) or secondary materials (F_{sec})

2208 A relative agronomic efficiency value below 1 indicates that that the fertiliser derived from
2209 STRUBIAS materials is a less effective plant P-source than a synthetic P-fertiliser derived
2210 from mined phosphate rock, and vice versa.

2211
2212 Data were grouped prior to meta-analysis to enable a broad ranging assessment of fertilising
2213 effectiveness of F_{sec} as a function of soil type, plant group, feedstock used for F_{sec} production,
2214 and variables related to the experimental design of the study (e.g. fertiliser regime, pot versus
2215 field trial, etc.). These parameters that discern groups were referred to as **grouping variables**.
2216 The relative agronomic efficiency for both response variables (RAE_{DMY} and RAE_{PUE}) was
2217 then calculated for a number of "cases" where all grouping variables (such as soil type and
2218 crop grown, crop harvest time, P application rate, etc.) are identical for both fertiliser
2219 treatments. Hence, the sole divergent variable for each case is the type of P-fertiliser.

2220
2221 Results were collected from the information provided by the STRUBIAS sub-group and from
2222 scientific literature. The number of studies and "cases" for recovered phosphate salts, ash-
2223 based materials and pyrolysis materials is indicated in Table 9. A significant number of
2224 studies were available for recovered phosphate salts and ash-based materials, whereas data
2225 coverage for pyrolysis materials was poor. Therefore, no hard conclusions on the agronomic
2226 efficiency of pyrolysis materials could be made. Hence, the **results for pyrolysis materials**
2227 **provide only a preliminary assessment and should be interpreted with the necessary**

2228 **caution.** The complete methodology and the references to the original works used for this
 2229 study is given in Box 1.

2230

2231 **Table 9: Number of studies and cases included for the meta-analyses on the relative agronomic**
 2232 **efficiency of P-fertilisers derived from recovered phosphate salts, ash-based materials and**
 2233 **pyrolysis materials.**

	recovered phosphate salts		ash-based materials		pyrolysis materials	
	RAE _{DMY}	RAE _{PUE}	RAE _{DMY}	RAE _{PUE}	RAE _{DMY}	RAE _{PUE}
studies	26	19	17	14	8	6
cases	173	104	117	94	31	16

2234

2235

2236

2237 **Box 1: Meta-analysis methodology**

2238

2239 *Data sources*

2240 Data sources that provided pertinent evidence from trustworthy sources in a manner that is
 2241 comprehensive, scientifically robust, objective and transparent were collected. In order to
 2242 safeguard transparency, confidential and non-publically available works were not considered
 2243 in this meta-analysis.

2244

2245 Studies that quantitatively reported DMY and/or PUE for recovered P and mineral P-fertiliser
 2246 treatments with a minimum of three experimental replicates were selected. Only assessments
 2247 that were performed on soils and plant species from boreal, temperate and Mediterranean
 2248 climate regions - within or outside Europe - were retained in order to provide an assessment
 2249 that is relevant for the EU-27 (i.e. geographic coordinated > 35°N/S). F_{prim} treatments
 2250 included different P fertilising substances, such as triple superphosphate, monoammonium
 2251 phosphate, diammonium phosphate, calcium super phosphate, single superphosphate, and
 2252 potassium phosphate. Dry matter yield and plant P uptake was mostly measured for
 2253 aboveground plant biomass yield, but some studies assessed whole plant biomass or specific
 2254 plant organs. If not directly reported, PUE was derived from the DMY and plant P
 2255 concentration, and concomitant standard deviations were calculated assuming error
 2256 propagation rules for normal distributions. When data were only provided in graphical
 2257 format, the corresponding authors of the studies were contacted to obtain the raw numerical
 2258 data. If not successful, relevant data points were extracted graphically from available figures.
 2259 When studies did not report measures of variance, the corresponding author was contacted
 2260 with a request to provide the raw data for the calculation of the standard deviation. For
 2261 studies in which it was not possible to acquire measures of variance, the uncertainty of the
 2262 missing effect sizes was drawn from a multiple imputation algorithm based on the
 2263 assumption of a common underlying variance, after which Rubin's rules were applied to get
 2264 the point estimates and standard errors of the meta-analysis results (Schwarzer et al., 2015).

2265

2266 Following studies were included in the assessment:

2267 Recovered phosphate salts: (Johnston and Richards, 2003; Hammond and White, 2005;
2268 Gonzalez Ponce and Garcia Lopez De Sa, 2007; Plaza et al., 2007; Massey et al., 2009;
2269 Weinfurtner et al., 2009; Ruiz Diaz et al., 2010; Cabeza et al., 2011; Gell et al., 2011; Liu et
2270 al., 2011; Antonini et al., 2012; Ackerman et al., 2013; Thompson, 2013; Achat et al., 2014;
2271 Uysal et al., 2014; Bonvin et al., 2015; Cerrillo et al., 2015; Vogel et al., 2015; Wragge,
2272 2015; Degryse et al., 2016; Hilt et al., 2016; Katanda et al., 2016; Liu et al., 2016; Sigurnjak
2273 et al., 2016; STOWA, 2016; Talboys et al., 2016; Vaneeckhaute et al., 2016).

2274 Ash-based materials: (Codling et al., 2002; Franz, 2008; Bird and Drizo, 2009; Kuligowski et
2275 al., 2010; Schiemenz and Eichler-Löbermann, 2010; Cabeza et al., 2011; Schiemenz et al.,
2276 2011; Komiyama et al., 2013; Rex et al., 2013; Weigand et al., 2013; Wells, 2013; Nanzer et
2277 al., 2014; Severin et al., 2014; Vogel et al., 2015; Wragge, 2015; Brod et al., 2016; Delin,
2278 2016; Reiter and Middleton, 2016).

2279 Pyrolysis materials: (Codling et al., 2002; Kuligowski et al., 2010; Müller-Stöver et al., 2012;
2280 Alotaibi et al., 2013; Collins et al., 2013; Ma and Matsunaka, 2013; Siebers et al., 2014;
2281 Reiter and Middleton, 2016).

2282

2283 *Effect size*

2284 Standardisation of the raw results was undertaken through calculation of the effect size. This
2285 allows quantitative statistical information to be pooled from, and robust statistical
2286 comparisons to be made between effects from a range of studies that reported results based
2287 on different experimental variables. The effect size was calculated as the natural logarithm of
2288 the response ratio R by using the following equation (Borenstein et al., 2009):

2289

$$\ln R = \ln RAE$$

2291

2292 The response ratio was then calculated for a number of "cases" where all grouping variables
2293 (such as soil and crop used, crop harvest time, P application rate, etc.; see below) are identical
2294 for both fertiliser treatments. The log response ratio and its variance was used in the analysis
2295 to yield summary effects and confidence limits in log units during the different meta-analysis
2296 steps. Each of these values was then converted back to response ratios to report the final
2297 results (Borenstein et al., 2009). All analysis were performed in the R software environment.

2298

2299 *Grouping variables*

2300 Data were grouped prior to meta-analysis to enable a broad ranging assessment of fertilising
2301 effectiveness of F_{sec} as a function of grouping variables that relate to soil type, plant group
2302 and management option. For all selected studies, quantitative information on following
2303 grouping variables were recorded: soil pH, soil texture, feedstock, sowed plant species,
2304 application form, harvest time after fertiliser application, soil P fertility, and experimental
2305 design. When specific parameters were not documented in the publication, the corresponding
2306 author was requested to provide the information; in case quantitative data was not available
2307 an expert opinion on parameter categorisation into groups was requested from the lead
2308 author.

2309

2310 *Soil pH* was classified as acidic for soils with a pH value less or equal than 6.0, and as
2311 neutral/basic for soils of pH greater than 6.0. *Soil texture* was classified as coarse (sand,
2312 loamy sand and sandy loam), medium (loam, silt loam, and silt) or fine (sandy clay, sandy
2313 clay loam, clay loam, silty sandy clay loam, silty clay and clay). *Feedstock* indicated the
2314 input materials from which the STRUBIAS material was derived (e.g. sewage sludge,
2315 manure). For ash-based materials, *post-processing* refers to the completing of a wet-digestion
2316 or thermal post-processing step to improve the plant P-availability of specific feedstocks (e.g.
2317 sewage sludge). *Plant groups* involved grasses (both annual and perennial species), oilseeds,
2318 cereals, legumes and others (leaf vegetable, cormous flowering plants, fruit vegetable, and
2319 pulse crops). *Application form* distinguished fertilisers that were applied as a powder or as
2320 granules. *Assessment time* was categorised as short and long for studies that harvested plants
2321 within and posterior to a period of 65 days of fertiliser application. In case of assessments on
2322 grasses, only the cumulative biomass and P uptake at the end of the experiment was
2323 considered. *Soil P status* was categorised as P-poor and P-rich, with a cut-off value of
2324 extractable Olsen-P content of 12.4 mg P kg⁻¹. The cut-off value was based on the average
2325 limit value for the "very low" P fertility category for a single soil within a number of
2326 European countries (Jordan-Meille et al., 2012). When other extractable P methods were
2327 applied, conversion methods and comparative relationships as given in Jordan-Meille et al.
2328 (2012), Neyroud and Lischer (2003) and McLaughlin (2002) were applied. When no
2329 extractable P data values were reported, expert opinions were requested from the
2330 corresponding authors. The approach applied based on a single cut-off value to discern soil P
2331 fertility for all soil-plant combinations is a simplification of a complex scientific matter
2332 (Jordan-Meille et al., 2012), but we are confident that it meets the objective of generally
2333 discerning settings in this meta-analysis study. *Experimental setting* separated pot from field
2334 studies. *Experimental design* assessed if the experimental study design involved the addition
2335 of plant nutrients, other than P, present in F_{sec} were also added in F_{prim}; "Fully balanced"
2336 corresponds to cases where all nutrients present in F_{sec} were also added in the F_{prim}
2337 treatments. "Deficient" refers to design where primary and secondary macronutrient present
2338 in F_{sec} were not added in F_{prim} (e.g. struvite as F_{sec}, but no addition of Mg in F_{prim}; poultry
2339 litter pyrolysis materials as F_{sec}, but no addition of N or K in P_{prim}).

2340
2341
2342 Results are represented as "forest plots" that graphically indicate the RAE_{DMY} (left Figure)
2343 and RAE_{PUE} (right Figure). The bars cover the 95% confidence interval, so error bars that do
2344 not cross the vertical 1 line indicate that F_{sec} is not significantly different from F_{prim}.

2345 2346 5.2.2 Recovered phosphate salts

2347 The overall results indicated a similar agronomic efficiency for recovered phosphate salts to
2348 mined and synthetic P-fertilisers. The mean values of RAE_{DMY} and RAE_{PUE} equal 0.99 and
2349 1.05, respectively (Figure 8), with the corresponding 95% confidence intervals overlapping
2350 the 1 value for both parameters. Regardless of soil pH, soil texture, feedstock, application
2351 form, plant type, soil P status, assessment time, and experimental design and setting, RAE_{DMY}
2352 and RAE_{PUE} values for recovered phosphate salts were not significantly different from 1. The
2353 RAE_{DMY} and RAE_{PUE} for struvite and dittmarite were not significantly different from 1, but

2354 the 95% confidence interval for RAE_{DMY} of calcium phosphates (grouping variable fertiliser)
2355 extended to a value marginally below 1 (0.995; Figure 8). No significant differences across
2356 selected groups were observed at the 95% level, albeit the effect of plant type was marginally
2357 significant (P: 0.06; data not shown) for RAE_{DMY} .

2358

2359 The analysis indicated that the **agronomic efficiency of precipitated phosphate salts is**
2360 **equal to that of mined and synthetic fertilisers. These results are consistent and**
2361 **generalisable across different settings, including soil and crop types, relevant for the**
2362 **European agricultural sector.** Although multi-year assessments fall beyond the scope of
2363 this meta-analysis, the results of Thompson (2013) and Wilken et al (2015) confirm the
2364 sustained long-term efficiency of precipitated phosphate salts as a P-fertiliser.

2365

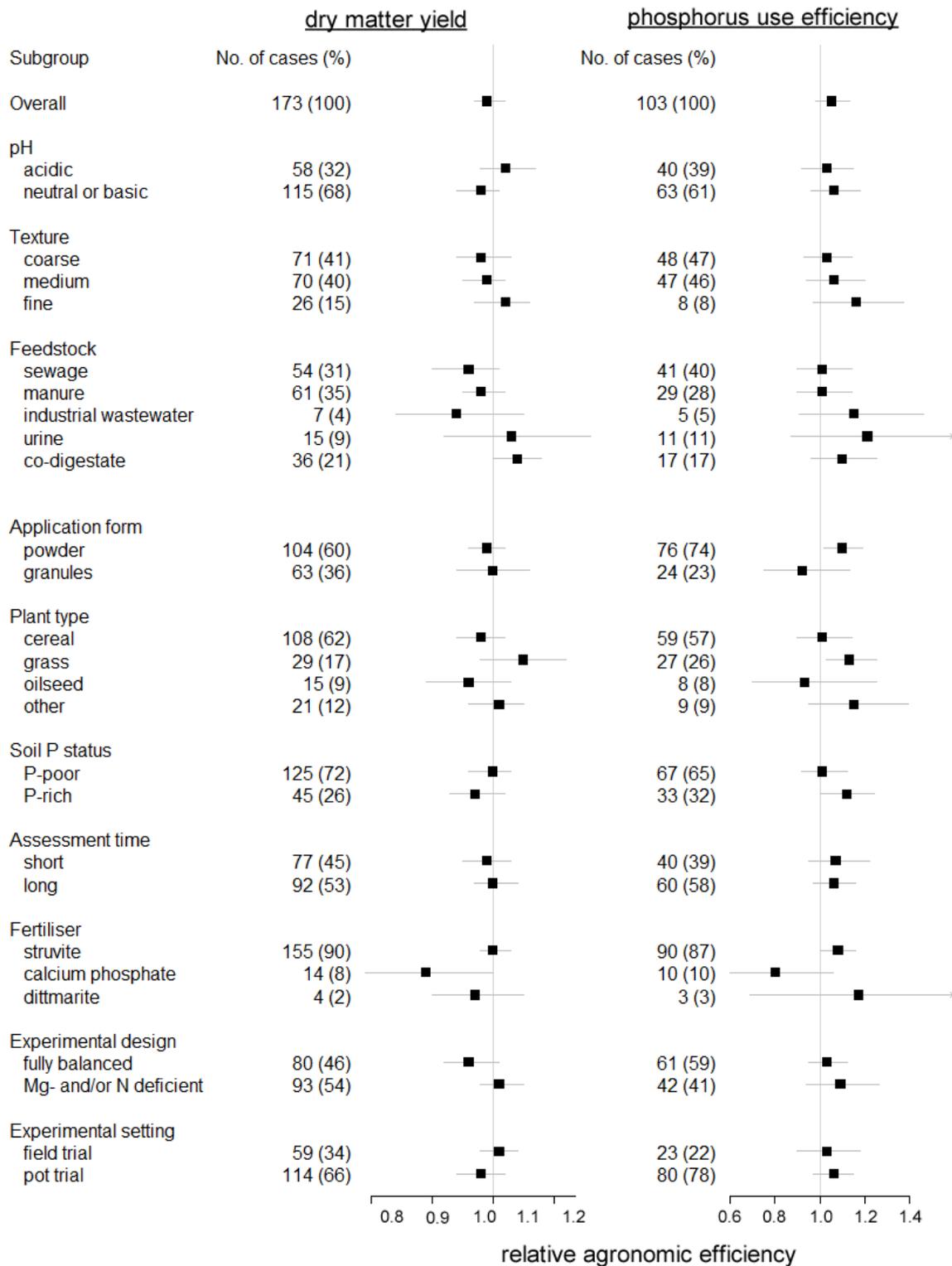
2366 Struvite is the most common precipitated phosphate salt, but some P-recovery processes
2367 target a **different end-material** such as dittmarite or dicalcium phosphates. The
2368 crystallization of calcium phosphates may involve the formation of metastable precursor
2369 phases, such as octocalcium phosphate and hydroxyapatite, which are less available to plants,
2370 especially at alkaline pH (Wang and Nancollas, 2008). Hence, the RAE of calcium
2371 phosphates can vary depending on the exact composition of the calcium phosphate phases
2372 included in the end-material. After application to the soil, calcium phosphates can also
2373 transform into more stable forms (Arai and Sparks, 2007), potentially further contributing to
2374 the wider RAE ranges observed for calcium phosphates than for struvite and dittmarite.

2375

2376 Unlike most mined and synthetic P-fertilisers, precipitated phosphate salts are water
2377 insoluble, but their solubility is increased in acid solutions (**Wilken et al., 2015**).
2378 **Nonetheless, our results indicated that soil pH had no significant effect on the relative**
2379 **agronomic efficiency.** Talboys et al. (2016) indicated that a complete dissolution of struvite,
2380 the most common precipitated phosphate salt, occurs in a relatively short term (<42 days)
2381 across a wider soil pH range of 5.0 – 8.0, a range relevant for most European soils. The rapid
2382 dissolution could also explain the observed non-significant effect of assessment time on
2383 RAE; the supplementary long-term effect of precipitated phosphate salts is thus not
2384 confirmed in this meta-analysis.

2385

2386



2388

2389 **Figure 8: The relative agronomic efficiency of recovered phosphate salts for the plant response**
 2390 **variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a function of**
 2391 **grouping variables. Results are presented as weighted mean (square) and 95% confidence**
 2392 **intervals (error bars).**

2393

2394 Plants also modify the rhizosphere pH as they exudate organic acids from their root biomass
2395 in significant quantities that can drastically lower pH in the plant root microenvironment.
2396 Talboys et al. (2016) indicated that organic acids have a major impact on the rate of
2397 dissolution of P from struvite, and that plants with root systems that exude large quantities of
2398 organic acids are more effective at taking up P from struvite granules. The exudates cause the
2399 dissolution of the precipitated phosphate salts in the vicinity of the plant root. Grasses
2400 exudate significantly more organic acids than common crops; estimates for the total
2401 allocation of photosynthates – a proxy for rhizodeposition - to roots are 50-70% higher for
2402 grasses than for cereals such as wheat and barley (Kuzyakov and Domanski, 2000). Hence,
2403 species-specific patterns of root exudation may explain the marginally higher RAE_{DMY}
2404 observed for grasses than for cereal and oilseeds.

2405
2406 In line with the observation that **feedstock** does not have a major impact on the chemical
2407 composition of the recovered phosphate salts, no input material-specific impacts on RAE
2408 were observed.

2409

2410 5.2.3 Ash-based materials

2411 **The overall mean effects for ash-based materials were 0.92 and 0.81 for RAE_{DMY} and**
2412 **RAE_{PUE} , respectively** (Figure 9). The 95% confidence intervals for both response variables
2413 indicated that the agronomic efficiency for ash-based materials was overall lower than for
2414 mined and synthetic fertilisers (Figure 9; 95% confidence intervals do not cross RAE value of
2415 1). The analyses for the different grouping variables indicated significant effects of feedstock,
2416 post-processing groups and assessment time for RAE_{DMY} and RAE_{PUE} ($P < 0.001$; data not
2417 shown). Ash-based materials derived from sewage sludge showed a significantly lower
2418 RAE_{DMY} and RAE_{PUE} than for ash-based materials derived from crop residues and poultry
2419 litter (Figure 9), but it should be deliberated that sewage sludge ash-based materials include
2420 both raw ashes and ashes that have been post-processed. Ashes that have been post-processed
2421 using wet-digestion and thermal manufacturing steps to improve their plant P-availability and
2422 reduce inorganic contaminants showed significantly greater RAE_{DMY} and RAE_{PUE} than raw
2423 sewage sludge ashes (Figure 9). The RAE_{DMY} values were 1.03 and 0.93 for materials
2424 subjected to wet-digestion and thermal post-processing steps (Figure 9). The RAE of F_{sec}
2425 derived from crop residues, poultry litter and pig manure did not differ from F_{prim} (Figure 9).
2426 Ash-based materials derived from wood and steel slags showed a low RAE_{DMY} and RAE_{PUE} ,
2427 but the results should be interpreted with precaution because of the low number of cases
2428 (Figure 9). A significant effect of assessment time on RAE_{DMY} and RAE_{PUE} was observed
2429 ($P < 0.001$; Figure 9), with values that are 20% (RAE_{DMY}) and 40% (RAE_{PUE}) lower in the
2430 long-term (>65 days) than in the short-term (<65 days). A significant effect of experimental
2431 design ($P: 0.04$) and experimental setting ($P: 0.003$) was observed for RAE_{PUE} (Figure 9). No
2432 significant effects of soil pH, soil texture, plant type and soil P status were observed, albeit
2433 the effect of soil pH on RAE_{PUE} was marginally significant ($P: 0.08$) (Figure 9).

2434

2435 Significant differences in the relative agronomic efficiency of ash-based materials were
2436 observed, primarily **dependent on the feedstock applied and the possible post-processing**

2437 **steps that were performed.** Ash-based materials consist of P-fertilisers with heterogeneous
2438 properties that control their behaviour and agronomic impacts in soils. Moreover, it should be
2439 taken into consideration that this study did not include fertilising products that are F_{sec} ash-
2440 derivatives (e.g. Ecophos® process, ICL RecoPhos® process, acidulation process; see Huygens
2441 et al. (2016) and Egle et al. (2016)) of equal chemical composition to that of F_{prim} . For such
2442 F_{sec} , an RAE value of 1 can reasonably be expected. The observed RAE results are not
2443 affected by soil pH, soil texture, application form, or soil P status, and different F_{sec} groups
2444 produced from a variety of feedstocks have an agronomic efficiency that is not significantly
2445 different from F_{prim} . Hence, **these observations validate that ash-based materials can**
2446 **deliver an effective alternative for mined and synthetic P-fertilisers in the European**
2447 **agriculture, but that the RAE is dependent on the properties of the produced ash-based**
2448 **end-material.**
2449

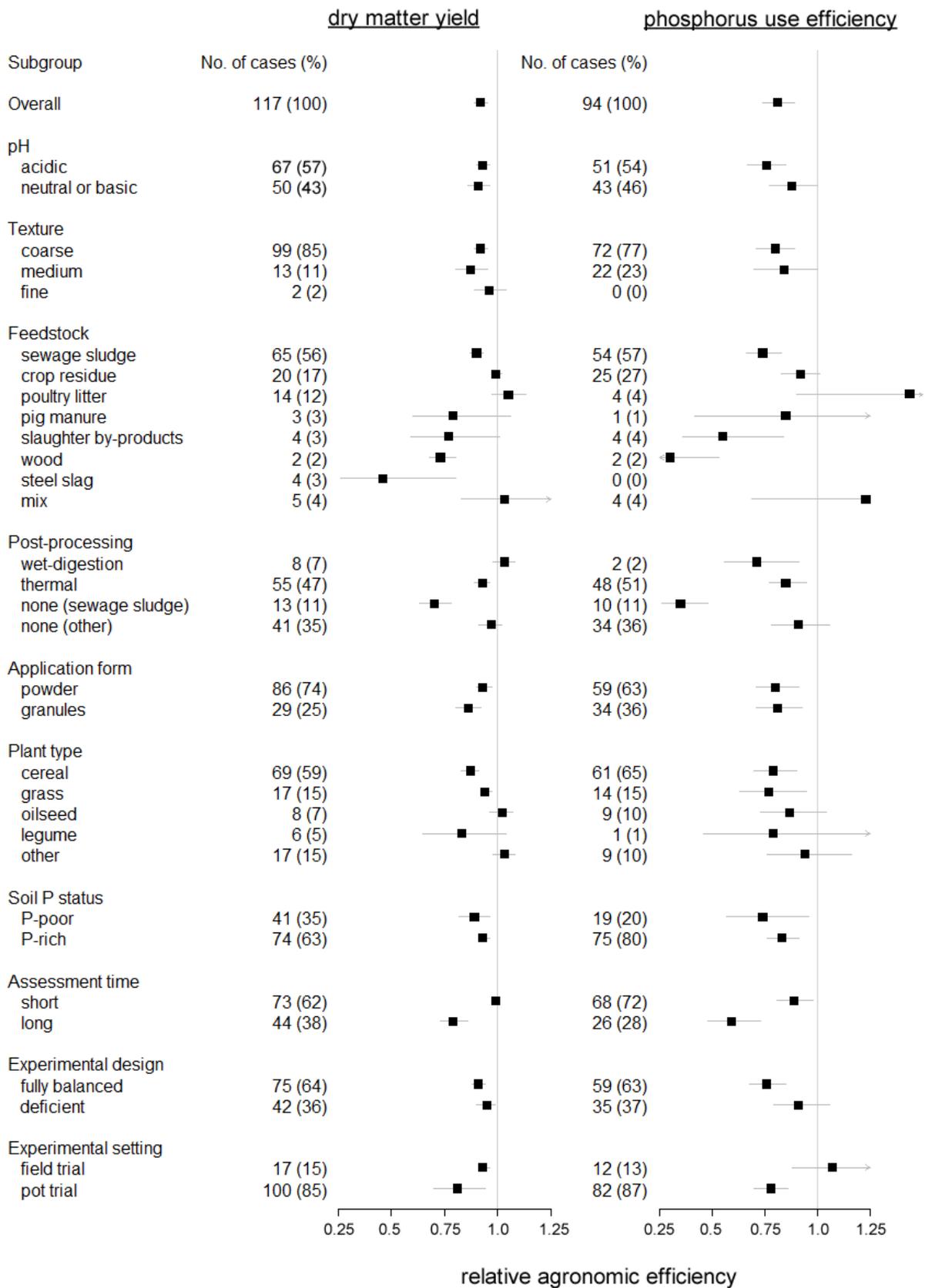
2450 It is observed that the effectiveness of ash-based materials in European soils **is not affected**
2451 **by soil pH.** The impact of pH on the P-dissolution depends on the elemental composition of
2452 the materials because P is strongly bond to Ca at high pH and to Fe and Al at low pH
2453 (Hinsinger, 2001; Tóth et al., 2014). Therefore, ash-based materials rich in Al/Fe could
2454 possibly be more effective in basic soils, whereas Ca-rich constituents could be more
2455 effective in acid soils. However, the high basic cation contents of some ash-based materials
2456 might buffer the acidity effect of the soil micro-environment, further obscuring the effect of
2457 the soil pH. Hence, no overall consistent effect of soil pH on RAE was observed due to the
2458 specific interactions between soil pH and ash-based fertiliser properties on P-release. Also, no
2459 differences were observed in RAE across plant types, indicating that possible differences in
2460 root exudation patterns of organic acids are not impacting the P-release patterns from ash-
2461 based materials.
2462

2463 The RAE varies considerably as a function of **feedstock, but these results require a**
2464 **cautionary interpretation as sample sizes are low for most groups, other than sewage**
2465 **sludge.** Crop residues show a high RAE value, but it should be considered that most results
2466 are derived from three studies that used a similar soil type (Schiemenz and Eichler-
2467 Löbermann, 2010; Schiemenz et al., 2011; Delin, 2016). For sewage sludge ashes, a post-
2468 processing step is often applied to increase P-availability, and to comply with legislative limit
2469 values for metals and metalloids. This analysis confirms that such **manufacturing processes**
2470 **starting from sewage sludge mono-incineration ashes clearly improve the plant**
2471 **availability relative to unprocessed sewage sludge ashes, and enable the transformation**
2472 **of sewage sludge ashes into efficient P-fertilisers.** Relative agronomic efficiencies close to
2473 1 can reasonably be expected materials resulting from wet-digestion post-processing,
2474 especially for these that have an equal chemical composition to that of mined and synthetic P-
2475 fertilisers. Thermal post-processing steps aim at separating P from other elements and to
2476 influence the crystal structure of the materials by isomorphic substitution of the PO_4^{3-} ionic
2477 group (by for example SiO_4^{2-} or CO_3^{2-}) affecting the reactivity of the final product and
2478 therefore plant P availability. The final products show similar characteristics as
2479 Thomasphosphate and Rhenaniaphosphate, and show overall good fertiliser efficiency.

2480 Thermal oxidation materials and derivatives **perform better in short-term experiments than**
2481 **in long-term studies** (> 65 days) (Figure 3). The plant-availability of the P in P-fertilisers is
2482 likely controlled by the coordinated cations of Ca, Mg Al and Fe to which PO_4^{3-} is bound. All
2483 these different ions are abundantly present in ash-based materials, although their relative
2484 abundance varies across end-materials. Complexes between phosphate and K, Ca, Mg, and S
2485 ions are relatively easily decomposed (Hinsinger, 2001; Tóth et al., 2014), and this more
2486 labile P-fraction is therefore likely to be released in the short term. Phosphate may, however,
2487 be unavailable to plants when strongly bound to particular trivalent cations in a stable matrix
2488 (Barrow, 1984; Hinsinger, 2001). The release of P from this more stable fraction could be
2489 limited, effectively decreasing the long-term P supply from ash-based materials. This
2490 contrasts with mined and synthetic fertilisers that are of a uniform chemical composition;
2491 such fertilisers can be expected to release P readily upon physical disintegration. The released
2492 P that is not readily taken up by plants can be adsorbed to soil minerals, with the nature of
2493 such reactions dependent on the pH and on the concentration of metal cations such as Ca, Fe
2494 and Al as well as organic and inorganic ligands (Hinsinger, 2001; Tóth et al., 2014). At a
2495 later time in the plant growing season, desorption of sorbed P can occur via ligand exchange
2496 reactions, especially if the P was bound in more labile soil P-complexes (Hinsinger, 2001).
2497 Such desorption processes could effectively contribute to a better long-term effect of mined
2498 and synthetic P-fertilisers compared to ash-based materials rich in trivalent cations.

2499
2500 Studies that supply primary and secondary macronutrients together with mined and synthetic
2501 P-fertilisers to ensure the equal supply of all different plant nutrients across treatments show a
2502 somewhat reduced relative agronomic efficiency, especially when PUE is considered as a
2503 response variable. On the other hand, results for the field studies performed in more realistic
2504 settings than those of pot experiments show better results. Both effects are potentially related,
2505 as field studies often apply a deficient experimental design where the broad range of
2506 secondary macronutrients and micronutrients present in ash-based materials are not added in
2507 the mined and synthetic P-fertiliser treatment. Hence, **these results indicate the importance**
2508 **of secondary macronutrients and micronutrients in achieving optimal agricultural**
2509 **yields**. It is often challenging to evaluate the supplementary fertiliser need for particular
2510 plant-limiting elements within the broad spectrum of secondary macronutrients and
2511 micronutrients. On condition that the excess application of micronutrients is avoided, the
2512 application of ash-based materials as P-fertilisers could provide the complementary benefit of
2513 supplying secondary macronutrients and micronutrients to enhance agronomic yields.

2514



2515

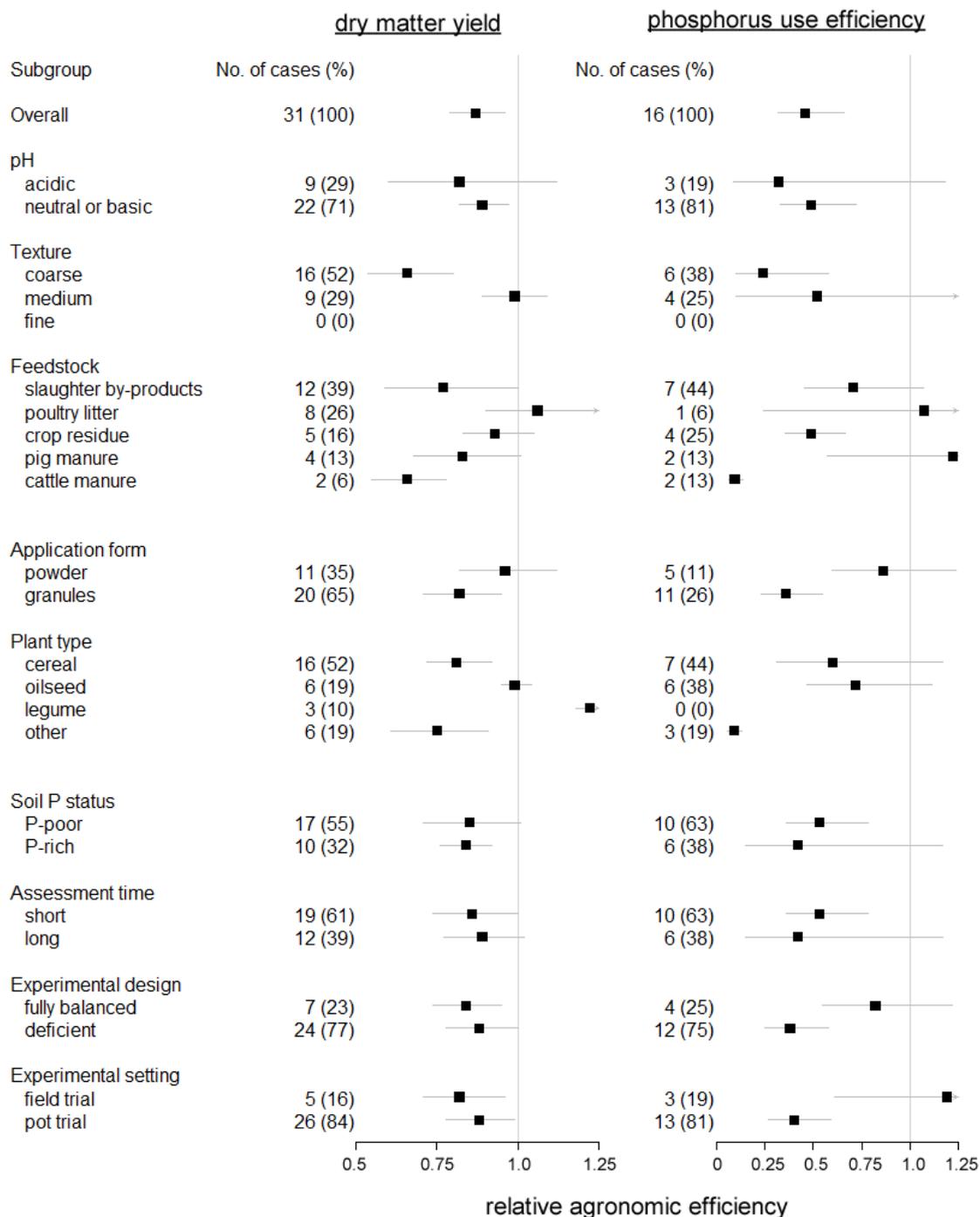
2516 **Figure 9: The relative agronomic efficiency of ash-based materials for the plant response**
 2517 **variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a function of**
 2518 **grouping variables. Results are presented as weighted mean (square) and 95% confidence**
 2519 **intervals (error bars).**

2520 5.2.4 Pyrolysis materials

2521 The overall results suggested a significantly lower agronomic efficiency for pyrolysis
2522 materials than for mined and synthetic P-fertilisers (Figure 10). **The overall mean effects for**
2523 **pyrolysis materials were 0.87 and 0.46 for RAE_{DMY} and RAE_{PUE} , respectively** (Figure
2524 10). The analyses for each of the grouping variables was constrained by the number of studies
2525 available; only the RAE values for neutral and basic soils and for pyrolysis materials that
2526 were applied in granulated form were derived from a minimum of 4 different studies and a
2527 number of cases greater than 10 for both response variables (RAE_{DMY} and RAE_{PUE} ; Figure
2528 10). For these groups, the RAE_{DMY} and RAE_{PUE} values pointed towards a significantly lower
2529 agronomic efficiency than for mined and synthetic P-fertilisers. The significant differences of
2530 specific groups such as those varying in soil texture (RAE_{DMY}), feedstock (RAE_{PUE}),
2531 application form (RAE_{PUE}), plant type (RAE_{DMY} and RAE_{PUE}), experimental design and
2532 setting (RAE_{PUE}) should be interpreted with caution because some of the contrasting groups
2533 have a low number of cases, often originating from a few studies. Therefore, only a marginal
2534 reduction of the size of the confidence interval of the underlying “true effect” across groups
2535 could be achieved, compared to the results from individual studies by applying the meta-
2536 analysis techniques. Hence, no conclusions can be drawn on RAE across pyrolysis materials
2537 applied to different soil types, feedstocks, application form and plant types. Figure 10
2538 enables, nevertheless, a standardised visual assessment of the RAE ranges observed across
2539 selected studies.

2540
2541 **Given the small sample size for pyrolysis materials, it is not pertinent to draw**
2542 **overarching conclusions for pyrolysis materials from the available data.** The properties
2543 of pyrolysis materials can vary widely, depending on the interactive effects between
2544 production process conditions and feedstock applied. Many groups, including pyrolysis
2545 materials derived from slaughter by-products, poultry litter, crop residues and pig manure,
2546 display an agronomic efficiency that is not significantly different from F_{prim} . The sole groups
2547 for which a relatively large number of data are available (at least 4 different studies and > 10
2548 cases) are neutral and basic soils and pyrolysis materials that have been applied in granulated
2549 form. For these groups, a lower agronomic efficiency than for mined and synthetic P-
2550 fertilisers is observed. Potentially, some of the documented high agronomic efficiencies after
2551 PY addition could be the result of a liming effect that increases soil P availability (Hass et al.,
2552 2012), or the result of the milling of the pyrolysis material that increases the P solubility in
2553 the otherwise stable pyrolysis matrix (Ma and Matsunaka, 2013). Therefore, future studies
2554 should focus on assessing the mechanisms that underlie documented potential positive plant
2555 responses, and evaluate the agronomic efficiency of pyrolysis materials in the same physical
2556 form as it will be applied under actual settings in agriculture. It is concluded that the current
2557 available data does not enable a comprehensive assessment of the agricultural efficiency of P-
2558 rich pyrolysis materials in relevant European agricultural settings, and that plant responses
2559 for P-rich pyrolysis materials can vary widely depending on the feedstock and production
2560 conditions of the pyrolysis materials, as well as on the soil and plant type under fertilisation.

2561
2562



2563

2564 **Figure 10: The relative agronomic efficiency of pyrolysis materials for the plant response**
 2565 **variables DMY (dry matter yield) and PUE (phosphorus use efficiency) as a function of**
 2566 **grouping variables. Results are presented as weighted mean (square) and 95% confidence**
 2567 **intervals (error bars).**
 2568

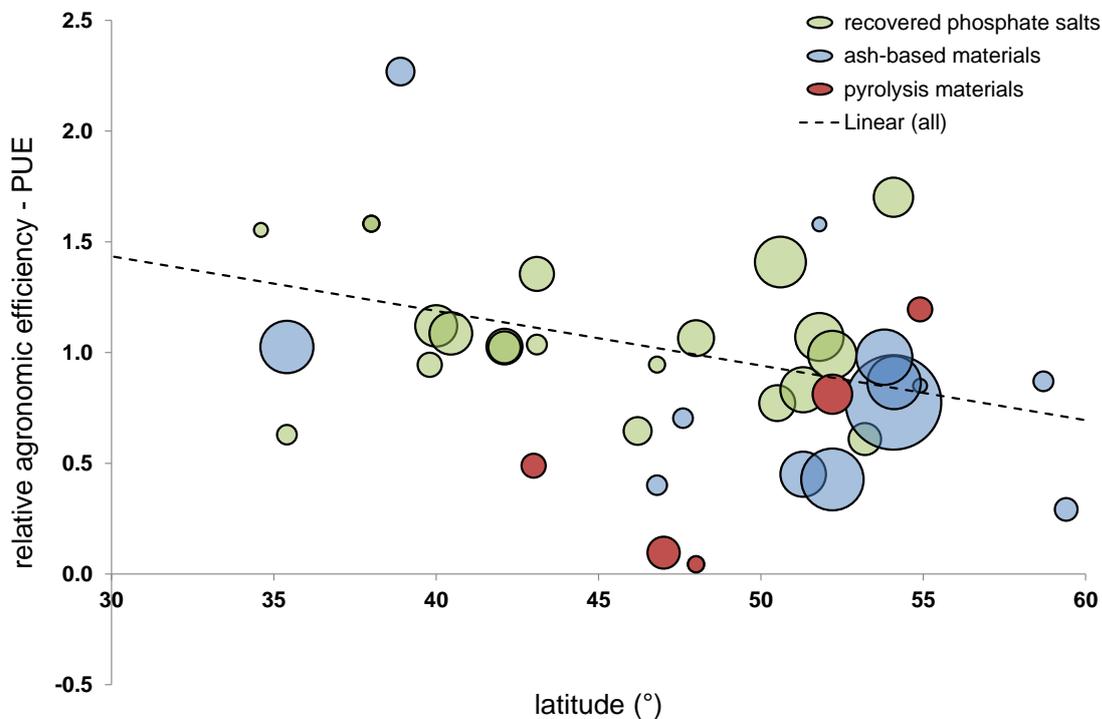
2569 5.2.5 Geographic scattering

2570 The results provided give an overview of the relative agronomic efficiency as a function of
 2571 soil and plant type, but fail to take into consideration the interactions and combinations of
 2572 those variables that occur in different geographic regions in Europe. Especially the effect of
 2573 the north–south position (i.e. latitude of the geographic coordinates) is relevant to consider,

2574 given that climate conditions (colder and drier soils at higher latitudes), soil texture (sandier
 2575 at higher latitudes), and soil pH (more basic at lower latitudes) vary significantly across this
 2576 gradient (Panagos et al., 2012; Ballabio et al., 2016). **A significant negative correlation**
 2577 **between geographic latitude on RAE_{PUE} was indicated ($P: 0.02$), with greater RAE_{PUE}**
 2578 **values observed in sites of lower latitudes than in higher latitudes** (Figure 11). Latitude
 2579 explained, however, only a minor share of the total variance observed ($R^2_{adj}: 0.14$).

2580
 2581 Concerns related to the effectiveness of water insoluble P-fertilisers in semi-arid and
 2582 Mediterranean regions may exist because some slow release P-fertilisers, such as phosphate
 2583 rock and meat and bone meal, do not dissolve readily in such soils (Bolland and Gilkes, 1990;
 2584 Elliott et al., 2007). The results of our work, however, reject such expectations for P-
 2585 fertilisers containing STRUBIAS materials in European settings as the RAE_{PUE} correlated
 2586 negatively to latitude (Figure 11). Therefore, **the effectiveness of F_{sec} for semi-arid and**
 2587 **Mediterranean European regions is supported.** The soil moisture patterns probably have a
 2588 negligible impact on the solubility of P-fertilisers containing STRUBIAS materials, as these
 2589 have a low water-soluble P fraction. Their solubility is mainly determined by the extent of
 2590 root exudation of the plants grown on the agricultural field. It can, however, be expected that
 2591 the solubility of water-soluble P-fertilisers is increased in the more northern latitudes
 2592 characterised by more moist soils due to the increased precipitation. Therefore, the agronomic
 2593 efficiency of mined and synthetic P-fertilisers could be higher for the higher latitudes,
 2594 resulting in decreased RAE ratios in the more northern regions. Other soil properties that vary
 2595 across latitude, such as soil texture and soil pH, did not have a significant effect on the RAE
 2596 for the STRUBIAS materials under study.

2597



2598

2599 **Figure 11: Bubble plot indicating the relationship between RAE_{PUE} and latitude. The size of the**
 2600 **bubbles represents the number of cases and relative weight for each data pair.**

2601

2602 **5.3 C-rich pyrolysis materials**

2603 A recent meta-analysis for C-rich pyrolysis materials indicated that, on average, C-rich
2604 pyrolysis materials did not increase plant yields relative to unfertilised control sites (Simon et
2605 al., 2017). The study was based on 598 cases documented in 44 different studies from
2606 temperate regions. It was observed that **C-rich biochar amendment to soils in temperate
2607 regions significantly decreased crop yield relative to controls (i.e. soils that did not
2608 receive any fertilising materials)**, averaging approximately 3% at a median biochar
2609 application rate of 30 t ha⁻¹. Jeffery et al. (2017) indicated that many arable soils in temperate
2610 regions are moderate in pH, high in fertility, and generally receive high fertiliser inputs,
2611 leaving little room for additional benefits from C-rich pyrolysis materials. Therefore, positive
2612 plant growth responses can mainly be expected in soils of lower fertility.

2613

DRAFT - WORK IN PROGRESS

2614 **6 Environmental and human health impacts**

2615 **6.1 Production phase**

2616 [to be completed for the final report]

2617

2618 **6.2 Use phase**

2619 [to be completed for the final report]

2620

DRAFT - WORK IN PROGRESS

2621 **7 Economic impacts**

2622 **7.1 Sales prices of P-fertilisers**

2623 7.1.1 DAP Free-on-Board as a benchmark for P–fertiliser prices

2624 Fertilisers, in the simplest of terms, have a very specific purpose: increasing crop yields per
2625 hectare. They achieve this purpose by compensating for any nutrient deficiencies in the soil,
2626 which could be due to a variety of reasons, from the geological nature of specific cropland
2627 areas, to weather events that remove topsoil nutrients, or again by bumper harvests that result
2628 in significant uptake of nutrients by plants themselves.

2629

2630 **This simplified reasoning suggests that, in an ideal market with perfect information, the**
2631 **price of fertilisers will be equal to the marginal yield gain expressed in monetary terms:**

2632

$$Price_{fert}^i = Price_{crop}^i * Area_{crop}^i * (Yield_{fert,crop}^i - Yield_{nofert,crop}^i)$$

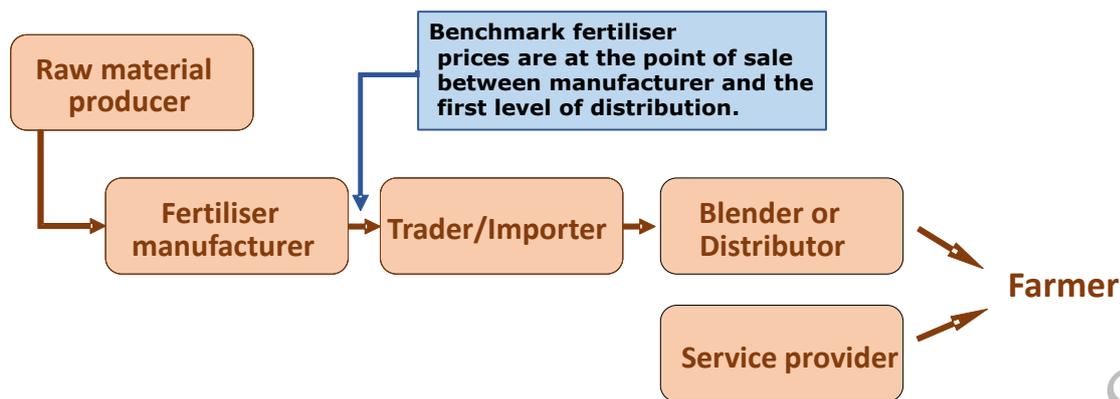
2633

2634 With $Price_{crop}$: the sales price for the crop as received by the farmer (Euro per tonne yield),
2635 $Area_{crop}$: the area of the cultivated crop (ha); $Yield_{fert,crop}$: the crop yield on fertilised areas
2636 (tonne yield per ha) and $Yield_{nofert,crop}$: the crop yield on fertilised areas (tonne yield per ha).

2637 This formula is very simple in its structure; however it already suggests a significant
2638 complication, which is that the true value of fertilisers is specific to individual patches of
2639 land, their specific nutrient balances, the crops planted, and their reactivity to fertiliser
2640 application. Also, as fertilisers consist of various nutrients (primary nutrients being nitrogen
2641 (N), P and potassium (K)), the yield gain for each individual fertiliser will depend on the
2642 nutrient content of the actual fertiliser mix applied, and again the actual yield gain will
2643 depend not only on the nutrient considered, but on the balance for other nutrients and the
2644 form in which each is applied. Such a pricing model, albeit undoubtedly interesting, is far
2645 from the scope of this study and can only be replicated on a very site-specific scale with in-
2646 depth agronomic analysis.

2647 A more meaningful and robust approach looks a few steps back in the **value chain**, as
2648 described in Figure 12. It is important to notice that all the agents involved are sometimes the
2649 same company, for example the Norwegian company Yara would act as a raw material
2650 supplier to its own manufacturing sites, and would sell its own products via its own
2651 distribution system, including providing services to farmers like soil sampling, agronomic
2652 analysis, and in some cases even direct application to the field. Individual companies will
2653 have various degrees of integration along the value chain.

2654



2655

2656 **Figure 12: Schematic overview of fertiliser value chain**

2657

2658 When looking at the European market specifically, the most common structure sees a
 2659 separation between fertiliser manufacturers and traders/importers, which in turn are in many
 2660 cases distribution companies or blenders themselves. **For this reason, this work uses trade-**
 2661 **based prices:** this allows identifying prices more accurately, as these are observed at a
 2662 consistent point. Moreover, focussing on trade values allows for the identification of product-
 2663 specific prices: farmers would receive tailored formulations often bundled with various
 2664 additives (e.g. micronutrients) and services, which makes farm-gate prices less transparent. In
 2665 contrast to farmers, traders and importers tend to focus on more “commoditised” varieties,
 2666 such as diammonium phosphate (DAP), which is a sufficiently standardised product globally.
 2667 Prices are given for **Free on Board (FOB) agreements**. This implies that the seller is
 2668 obligated to deliver the goods to a destination for transfer to a carrier designated by the buyer.
 2669 The location designation in the FOB trade agreement is the point at which ownership is
 2670 transferred from the seller to the buyer; it is most often the port located in the country of
 2671 phosphate rock extraction.

2672

2673 Generally speaking, traded materials at this benchmark **would then be considered as a raw**
 2674 **material for further processing**, for example in the form of bulk blends (for blenders) or
 2675 physical NPK compounds (for fertiliser manufacturers). Straight application of commoditised
 2676 products is also practiced, but blends and compounds account for the majority of actual
 2677 application to the soil.

2678

2679 For the price setting of P-fertilisers, it is important to determine which product acts as a
 2680 “P₂O₅ benchmark” against which other products are priced. **On a global basis, DAP is**
 2681 **usually acknowledged as the main price-setting product, due to its larger traded**
 2682 **volumes, which makes prices relatively more transparent.** Also, DAP ranks amongst the
 2683 fertilisers with the highest values of “total nutrient content” (N+P₂O₅+K₂O) across
 2684 commoditised products, meaning that it minimises freight costs per tonne nutrient compared
 2685 to most alternatives. Generally speaking, markets in Western Europe tend to feature DAP as
 2686 the main price-setting product, while Eastern Europe tends to show a preference for MAP
 2687 instead. Fertecon's market assessment for different EU Member States (France, Germany,
 2688 Italy, Poland and Romania) indicated that expressed on a P-basis, **trade-based price**
 2689 **differences between DAP and TSP are relatively minor (~ <10%), whereas the sales**

2690 **price for SSP is slightly higher** (~ +20%). This difference can be explained by the increased
2691 logistic cost associated to the transport of SSP (low P-content; 16-22% P₂O₅ versus 46% P₂O₅
2692 in TSP/DAP). Trade volumes for SSP are relatively low due to the inefficient transport
2693 logistics; therefore, local producers face less competition, and therefore can push prices to the
2694 upper end of any reasonable range.

2695

2696 7.1.2 Historical and forecast overview on P-fertiliser prices

2697 **All prices are given for the conventional farming sector in the EU-28.** P-fertilisers sold to
2698 specific niche sectors (e.g. fertiliser use in horticultural application, home gardening and
2699 growing media) might be associated to higher sales prices, but such price settings are not
2700 covered in this document.

2701

2702 Through the **1990s and in to the early 2000s** prices for P-fertilisers, using DAP as a proxy,
2703 could be categorised as being low. Margins in the industry were generally poor – in most
2704 years in the range of 5-10% would be typical. This enabled producers to trade **moderately**
2705 **profitably**, but critically there was very **little incentive for existing producers to invest in**
2706 **new capacity**, and no incentive at all for new producers to enter the market. As a
2707 consequence, there was only limited investment in P-fertiliser capacity, mostly by state-
2708 owned enterprises, and closures in other parts of the world ensured that there was no major
2709 increase in overall productive capacity.

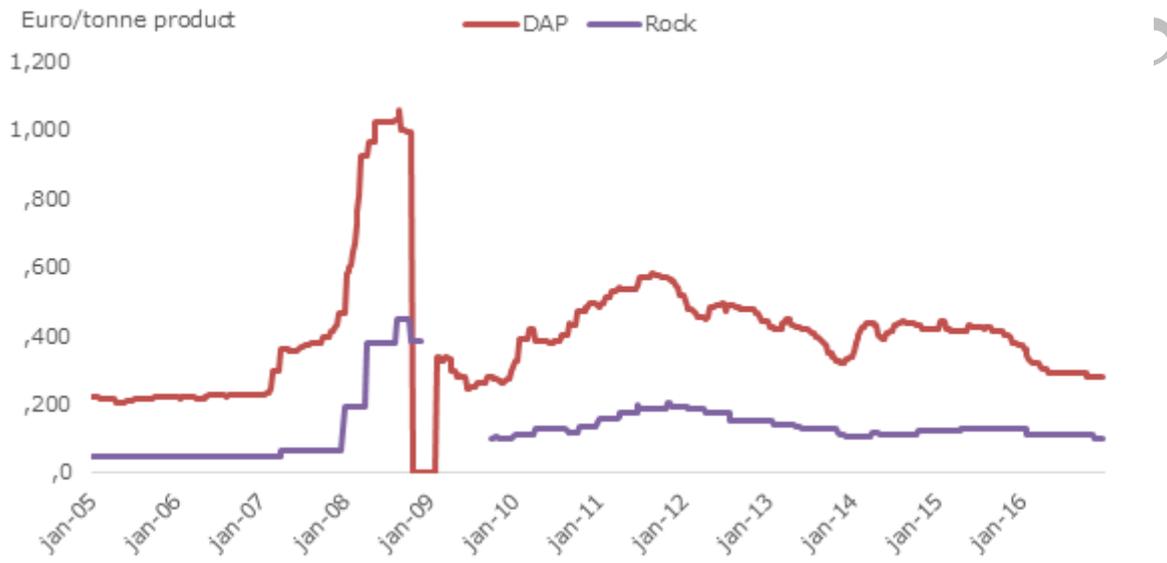
2710

2711 Following the Asian economic crash in 1997, economic growth around the world was strong
2712 over the 1997-2007 time period. Improving standards of living means that people generally
2713 consume more food (especially in developing nations) and can also afford more high-quality
2714 food especially proteins such as meat. Demand for cereals and other staple crops increases,
2715 both as food for humans and for animals which are then consumed by humans. **Increased**
2716 **demand for crops increased the use of fertiliser, which meant that fertiliser and P-**
2717 **fertiliser utilisation rates increased, and prices increased.**

2718

2719 The increase in margins during the period 2002 to 2007 began to encourage producers to
2720 consider projects and commence the building of P-fertiliser manufacturing construction sites.
2721 To build new phosphate fertiliser capacity will generally take between 36 and 48 months
2722 once construction begins, and clearly there will normally be a few years of planning required
2723 in advance, especially if it is for a greenfield development (as opposed to expanding an
2724 existing site). Therefore, **during the super-heating of the global economy in 2007 and**
2725 **2008, demand exceeded the industry's ability to supply, and consequently prices**
2726 **increased significantly.** In 2004 the average price of DAP on the basis of FOB Morocco was
2727 \$235/t (189 Euro/tonne), in 2007 it was \$425/t (310 Euro/tonne) and in 2009 it was \$1090/t
2728 (782 Euro/tonne). With the economic crash in late 2008 reality re-asserted itself, and in 2009
2729 price levels declined. Producers tried to hold on to gains for a period, but over 2009 and 2010
2730 it was very clear that if they were to do so it would be at the expense of production volumes.
2731 From 2011 onward there have also been the commissioning of projects which were planned
2732 in the mid-years (and later) of the 2000s. The other key (and related) structural change in the

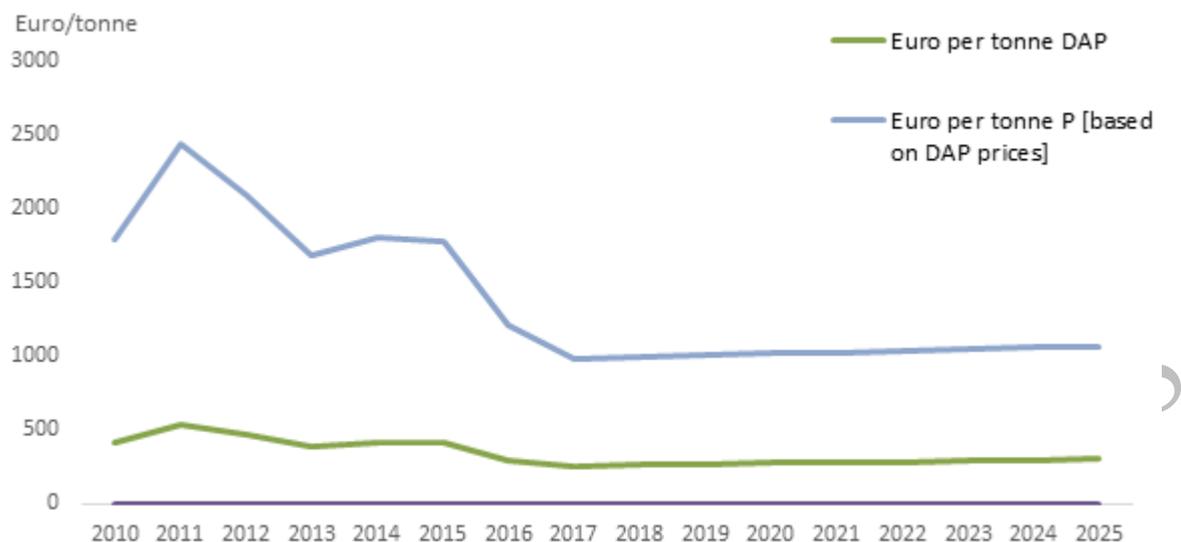
2733 market has been the build-up of production capability in China, which has meant that China
 2734 has gone from a net P-importer in the late 1990s to being a significant P-fertiliser exporter.
 2735 Although capacity has been decommissioned in less cost-efficient locations, P-fertiliser
 2736 production has returned to a position of net surplus, with a corresponding reduction in prices.
 2737 Figure 13 shows the price evolution for DAP and rock on the basis of FOB Morocco / North
 2738 Africa. The breaks in the prices were effectively when there was no market; producers
 2739 wanted prices buyers were unprepared to pay.
 2740



2741
 2742 **Figure 13: Price evolution for diammonium phosphate (DAP) and phosphate Rock (Euro/tonne**
 2743 **product; assuming an average exchange rate of 1.2 Euro/US dollar; prices given for Free on**
 2744 **Board agreements) (Source: Fertecon)**
 2745

2746 Looking forward, Fertecon is expecting the market to maintain the current (2017) level of
 2747 balance through to 2025, i.e. that growth in demand will be off-set by increased capacity to
 2748 supply, and therefore there will not be any significant improvement on utilisation rates in the
 2749 industry. This means that price levels will be maintained at levels which provide a margin for
 2750 the major producers, but will also progressively eliminate some of the marginal capacity.
 2751 Therefore, DAP prices are estimated to increase moderately from 2017 onwards with an
 2752 average price increase of 1-2% per year (green line, Figure 14).

2753
 2754 The price per tonne P in mined and synthetic P-fertilisers is evaluated based on the DAP
 2755 prices. For the calculations, the value of N present in DAP is subtracted from the DAP price,
 2756 after which the N-devaluated DAP is expressed on a P-basis. The N in DAP is evaluated
 2757 based on the ammonia price (381 US dollars per tonne ammonia-N, or 69 US dollars for the
 2758 18% N in DAP). Also, a constant 1.2 Euro/US dollar exchange rate is used in these
 2759 calculations. **A price of 988 Euro per tonne P FOB is indicated for the year 2017.**



2760

2761 **Figure 14: Fertecon DAP Price Forecast to 2025 expressed per tonne of DAP and per tonne P**
 2762 **(FOB Morocco; exchange rate of 1.2 Euro/US dollar applied by JRC)**
 2763

2764 The 2025 FOB forecast is also within the range of prices experienced prior to the 2007-2009
 2765 super-cycle, when adjusted for inflation. This is a relevant comment: there are many bodies
 2766 that describe current price levels as low. This is factually accurate in comparison to recent
 2767 years, but not in the historical context. In comparison to the period 1990 to 2005, **the current**
 2768 **price level might be better described as ‘normal’.**

2769

2770 7.1.3 Price setting for STRUBIAS materials

2771 Given the lack of legal outlets for many STRUBIAS materials in many EU Member States,
 2772 **these materials are at present not valorised within a stable reference framework.** At
 2773 present, the volumes of STRUBIAS materials on the internal fertiliser market are very low,
 2774 and mostly delivered to specific niches of the internal agricultural market. Depending on the
 2775 legal framework, market access is only granted to specific STRUBIAS materials, mostly
 2776 under national legislation. Therefore, it is challenging to provide a meaningful evolution of
 2777 the sales prices for a given fertilising product containing recovered materials in the EU
 2778 observed in order to determine the main factors affecting prices of STRUBIAS materials and
 2779 their relative importance.

2780 This section aims at estimating the potential value of STRUBIAS materials and incineration
 2781 ashes that can be used as raw materials by the fertiliser industry. Rather than giving an
 2782 overview of the expected sales prices, this section provides **a benchmark for the economic**
 2783 **valuation of STRUBIAS materials**, and focusses on the drivers that can be expected to
 2784 affect sales prices for **use in conventional agriculture.**

2785 It is also important to note that the values are presented for Cost and Freight (CFR)
 2786 **agreements** to downstream users, and thus include the shipment costs to **the downstream**
 2787 **processor or user.** For the producer of STRUBIAS materials the potential revenues will be

2788 lower, as any distribution costs will need to be deducted. Particularly with regard to materials
2789 of low economic valuation (e.g. incineration ashes as an intermediate raw material within the
2790 P-fertiliser production chain), it is important to recognise that the indicated values are CFR.

2791

2792 In this assessment, an important distinction is made in estimated pricing **between products**
2793 **sold as raw materials for the fertiliser industry and products sold directly as fertilisers.**
2794 Importantly, it is generally not possible to isolate prices for each specific end-use when the
2795 same product can be used in various ways.

2796

2797 • **Raw materials for chemical processing:** This case mainly refers to mono-incineration
2798 ashes derived from P-rich input materials such as sewage sludge, meat and bone meal,
2799 and possibly manure fractions. Sewage sludge ashes are not useable as fertilisers directly
2800 due to the metals/metalloids contained, meaning that a lower price per tonne P_2O_5 can be
2801 expected than for finished fertiliser products as various additional costs need to be
2802 incurred before reaching the end point in the manufacturing chain. For ashes derived from
2803 meat and bone meal and manure, possible post-processing could further improve the plant
2804 availability of the P contained. As such manufacturing steps involve large-scale industrial
2805 manufacturing, the specific chemical composition of the product sold is crucial, as
2806 relatively small variations in material quality (e.g. P-content, Al/Fe content) can result in
2807 significant increases in operating costs for the consumers of these materials. The price
2808 setting for such materials is therefore largely **determined by the price setting of CFR**
2809 **phosphate rock** that is consumed as a source material by downstream manufacturers of
2810 complex P-fertilisers.

2811 • **Fertilisers ready for sale:** this is the case of products such as **DAP, MAP or TSP.** In
2812 most cases, no further processing is required, meaning that higher prices per tonne P_2O_5
2813 can be expected compared to raw material prices; the expected sales price includes the
2814 manufacturing costs already occurred throughout the value chain, plus some profit margin
2815 of all actors involved within the value chain. Physical qualities like particle size or
2816 hardness, or the content of impurities, can play a role in pricing. The chemical
2817 composition of such products is, generally speaking, homogenised and standardised.
2818 Here, the **price setting occurs relative to finished fertiliser products already on the**
2819 **market**, and the value of P is likely to be linked to the value of P in a multinutrient
2820 fertiliser such as DAP.

2821 • **P-materials for secondary compounds:** this is **somewhat in the middle between the**
2822 **previous two categories.** Some producers purchase products (e.g. DAP), grind it into
2823 smaller particles, and re-granulate a mix of various particles to obtain a product
2824 containing various nutrient grades. Contrary to bulk blends (which are just a physical mix
2825 of individual fertilisers), these re-granulated products have a uniform nutrient content in
2826 each granule. Since the raw materials for this process need to be ground, physical
2827 characteristics play almost no role in price-setting, and **the nutrient content is by far**
2828 **and large the main determinant of traded value.** A condition is, however, that the
2829 materials have characteristics that make them suitable for blending. **Buyers of such**
2830 **products often are able to obtain a relatively lower price per tonne P_2O_5 compared**

2831 **to products sold as finished fertilisers, mainly by targeting material with poorer**
 2832 **physical characteristics.** A relevant example for such a case could be powdered
 2833 struvites. Hence, for STRUBIAS materials that will be used as raw materials for
 2834 secondary compounders, the price setting for the P contained in the STRUBIAS materials
 2835 is likely to occur relative to P-fertiliser products used by blending companies. After the
 2836 application of a discount, the price for such materials could mirror the price of finished
 2837 fertilisers on the market.

2838
 2839 **The value of STRUBIAS materials is likely** to be determined to a significant extent by the
 2840 P content contained in the material. The benchmark for the valuation of incineration ashes
 2841 that will be used as intermediates in the P-fertiliser production chain is **phosphate rock**
 2842 ($P_{intermediate}$ in Table 11), whereas end materials of STRUBIAS production processes (i.e. the
 2843 CMC material) will be benchmarked relative to materials for blending or finished fertilisers,
 2844 or **DAP** (P_{final} in Table 11). The current CFR market prices for DAP and phosphate rock,
 2845 expressed as Euro per tonne P contained in the material, are given in for different EU
 2846 Member States.

2847

2848 **Table 10: Value of P present in DAP and phosphate rock from Morocco (Euro per tonne P,**
 2849 **CFR Morocco) assessed for different EU Member States for the year 2017 based on import**
 2850 **prices (Source: Fertecon; exchange rate of 1.2 Euro/US dollar applied by JRC).**

	France	Germany	Italy	UK	Poland	Romania	Average
DAP	1213	1397	1213	1234	1198	1256	1252
phosphate rock	558	685	594	852	539	665	649

2851

2852 The price as estimated based on the P content is further expected to be modified by price
 2853 premiums and price discounts.

2854 • **Price premiums** could possibly apply to materials that are low in metals/metalloids,
 2855 mainly recovered phosphate salts. The use of recovered phosphate salts in fertiliser
 2856 blends could effectively the Cd content in P-fertilisers, and avoid as such the need for
 2857 decadmiation (a cost estimated of about 27 – 68 Euro per tonne P) or the reliance on
 2858 possibly more expensive phosphate rocks, low in Cd content. Supplementary nutrients
 2859 in STRUBIAS fertilisers are valued for fertilisers ready for sale and raw materials for
 2860 secondary compounds used by compounders or blenders who would be able to fully
 2861 monetise the nutrient values in the formulation. **Magnesium** is valued at 130 Euro per
 2862 tonne Mg. An additional Mg value for STRUBIAS materials containing Mg (e.g.
 2863 struvite) will be added. **Nitrogen** is valued at around 320 Euro per tonne across EU
 2864 Member States. The value of N is based on price of ammonia as a source of N. An
 2865 additional N value for STRUBIAS materials containing N (e.g. struvite) will be
 2866 added. For struvites, the combined monetary value for Mg and N will, however, be
 2867 relatively lower than the monetary value for P (<20%).

- **Price discounts** are expected to apply for STRUBIAS materials that i) have a reduced or unknown relative agronomic efficiency compared to mined and synthetic P-fertilisers, ii) are non-granulated, iii) have a lower nutrient and P-density that increases fertiliser distribution and application costs, iv) show a reduced suitability for its use in fertiliser blends, and v) are generally associated to a reduced degree of consumer confidence.

Examples of possible benchmark CFR prices based on their P content for selected STRUBIAS materials in conventional agriculture are given in Table 11.

Table 11: Benchmark CFR prices for the valuation of incineration ashes and STRUBIAS materials based on the P contained and other relevant price setting factors (Euro per tonne material).

material	basic price		price premium	price discount
	P _{intermediate}	P _{final}		
granulated struvite (12.6% P, 9.9% Mg, 5.7% N)	-	158	low in metals, N & Mg value of 28 Euro/t, granulated material	not applicable
powdered struvite (12.6% P, 9.9% Mg, 5.7% N)	-	158	low in metals, N & Mg value of 28 Euro/t	not granulated
sewage sludge ashes (9% P, low in Al/Fe content)	58	-	not applicable	not applicable
poultry litter ashes (5.5% P,)	-	69	PK fertiliser	low nutrient density, agronomic efficiency tested on limited soil and plant types
TSP derived from sewage sludge ash (20% P)	-	250	low in metals, granulated material	not applicable
Thomasphosphate-like ashes (e.g. AshDec, 7.5% P)	-	94	low in Cd	low nutrient density, agronomic efficiency tested on limited soil and plant types

For some STRUBIAS materials, the target market for pyrolysis materials may not be the conventional agricultural market. Specific materials of all SRUBIAS material groups could possibly make a market entry niche markets where fertilising products are traded at higher prices (e.g. organic farming, horticulture, and growing media). In organic farming, the absence of competition from mined and synthetic P-fertilisers could positively impact upon the sales prices of the STRUBIAS materials. Hence, in niche markets, **the specificity of the source materials and the possible environmental impacts of STRUBIAS production**

2889 **processes on natural resources can be expected to impact upon the sales prices of the**
2890 **STRUBIAS materials.**

2891 It is expected that the future evolution in sales prices will closely reflect the expected price
2892 evolution for phosphate rock (intermediate raw materials) and P value in finished fertilisers
2893 (DAP) as given in section 7.1.2. For these materials, a negligible increase for the period 2016
2894 - 2025 is expected. The future **prices for STRUBIAS materials are therefore expected to**
2895 **remain stable.** Nonetheless, the consumers' confidence in STRUBIAS materials and the field
2896 verification of the presumed agronomic efficiency in the relevant agricultural sectors could
2897 further impact the future prices for STRUBIAS materials.

2898 Based on this assessment, it is clear that **STRUBIAS materials can vary largely in pricing,**
2899 **depending on the STRUBIAS material group, the characteristics of the output material,**
2900 **and target markets.**

2901

2902 Question 1 to STRUBIAS sub-group:

2903

2904 Please provide an indication of:

- 2905 • the **sales prices** of STRUBIAS materials and mono-incineration ashes on the market
2906 (Euro per tonne material and P concentration, or Euro per tonne P; indicate if prices are
2907 "Free on Board (FOB)" or "CFR (Cost and Freight)" with an indication of the price for
2908 transport).
- 2909 • Indicate also the **physical form** of the material (powder, granules, other relevant physical
2910 parameters), and **to whom materials are sold** (blending companies, retailers, end users,
2911 etc.).
- 2912 • If available, please provide an **evolution** of the average sales prices in the last decade in
2913 order to determine the *main factors affecting fertiliser price* and their relative importance.

2914

2915 **7.2 Production cost for STRUBIAS materials**

2916 [to be completed for the final report]

2917

2918 **7.3 Compliance costs**

2919 [to be completed for the final report]

2920 Question 2 to STRUBIAS sub-group:

2921 Please provide information on the following elements that form part of the compliance costs:

- 2922 • Cost for REACH registration for fertiliser end-material that will be brought on the
2923 market.
- 2924 • Cost for compliance under already existing national end-of-waste or similar regimes that
2925 enable a market entry for fertilising products derived from STRUBIAS materials.

- 2926 • Estimated cost for compliance for P-fertilisers derived from primary raw materials.
- 2927 • For facilities that process waste-based materials, information on the cost associated to
- 2928 acquiring waste permits in different EU Member states for non-hazardous and hazardous
- 2929 waste materials. Notably, the costs associated to complying with the obligation for an
- 2930 establishment or undertaking carrying out waste management operations to have a permit
- 2931 or to be registered in accordance with Article 23-26 of the Waste Framework Directive
- 2932 2008/98/EC.
- 2933 • Cost of sampling and analysis through accredited laboratories:

2934 Recovered phosphate salts:

- 2935 - Nutrients: P, Ca, Mg, citric-acid P
- 2936 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn
- 2937 - Persistent organic pollutants: PAH₁₆
- 2938 - Biological pathogens: E. coli or Enterococcaceae & Salmonella spp.
- 2939 - Others: macroscopic impurities, dry matter content, particulate matter < 100 µm.

2940 Ash-based materials:

- 2941 - Nutrients: P, K, Ca, Mg, S, citric-acid P
- 2942 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn, B, Ba, Co, Mn, Mo,
- 2943 Sb, V
- 2944 - Persistent organic pollutants: PAH₁₆, PCB, PCDD/F
- 2945 - Others: pH and neutralising value

2946 Pyrolysis materials:

- 2947 - Major elements: C, Corg, P, K, Ca, Mg, S
- 2948 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn, Ba, Co, Mo, Sb, V
- 2949 - Persistent organic pollutants: PAH₁₆, PCB, PCDD/F
- 2950 - Biological pathogens: E. coli or Enterococcaceae & Salmonella spp.
- 2951 - Other: pH, neutralising value, macroscopic impurities, particulate matter < 100 µm,
- 2952 particle density, volatile organic matter, specific surface area earthworm avoidance test (ISO 17512)
- 2953 Where analysis packages are available (e.g. sampling + analysis of a series of metals, PAH₁₆, PCB
- 2954 and PCDD/F), please clearly state what the package contains and its cost.

- 2955
- 2956 • Measurement standards currently applied (national standards, ISO/EN standards, etc.)
- 2957
- 2958
- 2959

2960 **7.4 Possible economic benefits and drawbacks of producing fertilising products**

2961 **containing STRUBIAS materials**

2962

2963 Question 3 to STRUBIAS sub-group:

2964 Please provide information, preferably in a quantitative manner, on following possible

2965 economic benefits and drawbacks of producing fertilising products containing STRUBIAS

2966 materials compared to equivalent mined and synthetic inorganic fertilising products.

2967
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2982

- reduced waste compliance costs (e.g. changes in the economic valuation of sewage sludge ashes, etc.);
- reduced externalities (e.g. avoided costs due to eutrophication, positive effects on human health due to reduced contaminant levels, etc.);
- potential job creation in production and downstream fertiliser distribution and farmer's cooperatives; please relate expected STRUBIAS production volumes to number of persons employed.
- impacts on the rural economy;
- benefits of restoring soil organic carbon for soil fertility;
- cost associated to new logistics for recovered nutrient products;
- implications for the restructuring the production and distribution of fertilising products;
- agricultural equipment adaptations.

DRAFT - WORK IN PROGRESS

2983 **8 Market aspects and outlook for the year 2030**

2984 In the proposal for the Revised EU Fertiliser Regulation, fertilising products are classified in
2985 product function categories (PFCs) that are in line with their intended function. Given the
2986 different intended uses for these STRUBIAS materials, this document is structured into
2987 different **sub-sections that cover uses of such materials in P-fertilisers (section 8.1 and**
2988 **8.2)** or in **liming materials, soils improvers, growing media and plant biostimulants**
2989 **(section 8.3)**. The sections 8.1 and 8.2 on P-fertilisers cover materials with a minimum P-
2990 content of 3% and 2% P₂O₅, the P-threshold values for inorganic and organic/organo-mineral
2991 P-fertilisers, respectively. Market aspects for materials with a lower P-content are covered in
2992 section 8.3.
2993

2994 **8.1 Market aspects and outlook for P-fertilisers**

2995 8.1.1 Phosphate rock as the major source for P-fertilisers

2996 The current market of P-fertilisers is **dominated by synthetic inorganic materials that have**
2997 **been derived from phosphate rock**. Specific materials such as unprocessed phosphate rock,
2998 meat and bone meal, and guano can be used as alternative P-fertilisers, but their use is limited
2999 in quantities applied and agricultural sectors covered. The future outlook of P-fertilisers is
3000 based on the evolution of supply and demand of mined of synthetic and mined fertilising
3001 products that currently dominate the market of P-fertilisers.
3002

3003 There are three classical routes for the **production process of P-fertiliser from phosphate**
3004 **rock** (European Phosphate Fertilizer Alliance, 2017):
3005

- 3006 • The first route treats phosphate rock with sulfuric acid to create phosphoric acid, which is
3007 then used to produce **Diammonium phosphate (DAP) or Monoammonium phosphate**
3008 **(MAP)**. DAP is typically 18-46-0 (i.e. contains 18% N, 46% P₂O₅ and 0% K₂O), whereas
3009 MAP can be between 10-50-0 and 11-55-0. MAP and DAP can be used as the final
3010 fertiliser or as input for NPKs. The main downside of this process is that some
3011 phosphogypsum is created as a residue, which raises environmental concerns and also
3012 leads to some P being lost. The main benefit of this route is that it includes an
3013 intermediate stage where phosphoric acid is formed, which currently is the only potential
3014 stage where decadmiation technologies could possibly be applied to remove cadmium.
- 3015 • The second route also uses sulfuric acid, but in smaller quantities in relation to phosphate
3016 rock, which results in superphosphate (**SSP**, typically between 0-16-0 and 0-22-0) or
3017 triple phosphate (**TSP**, typically ranging between 0-44-0 and 0-48-0). These can be used
3018 as final fertilisers, or as inputs for NPK fertilisers.
- 3019 • The third route is the so-called **nitrophosphate** route, which consists of treating
3020 phosphate rock with nitric acid to obtain compound fertilisers. Phosphoric acid and
3021 calcium nitrate are formed as intermediary products, which then react. There are generally
3022 two variations of this process (“Odda” process or mixed-acid process).

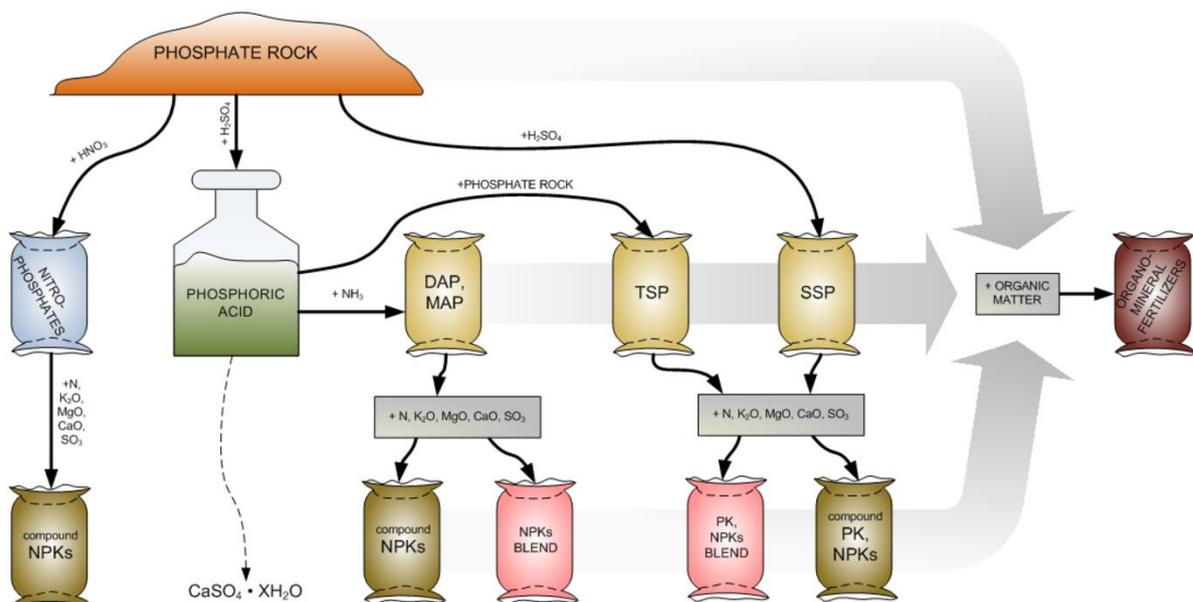
3023

3024 The resulting materials from these three routes can then be used for the production of NPK
3025 fertilisers:

3026 ○ **Complex NPK fertilisers** are produced by a chemical reaction in a chemical plant.
3027 For example, an NPK fertiliser can be made by reacting nitric acid with phosphate
3028 rock to make an ammoniated phosphate, and adding potassium chloride (KCl) and
3029 granulating. The resulting product will have the same proportions of N, P and K in
3030 each granule. Complex plants are expensive to build, but can produce the lowest cost
3031 NPK products. They are relatively inflexible, being best operated making a small
3032 number of large volume grades.

3033 ○ **Compound NPK fertilisers** are physical mixes. Ingredients such as ammonium
3034 nitrate (AN), monoammonium phosphate (MAP) and KCl can be mixed in the correct
3035 proportions for the amounts of N, P and K required. This mix is then ground down to
3036 a fine powder, thoroughly mixed, and usually granulated using e.g. steam granulation.
3037 This ensures that the desired N, P and K proportions are present in each granule, but
3038 without involvement of wet chemistry. Compound plants require moderate
3039 investment, and whilst still benefiting from economies of scale, are generally smaller
3040 and more flexible than complex plants, making a wider variety of products.

3041 ○ **NPK Blends** are physical mixes of different fertilisers, such that the proportions of N,
3042 P and K correspond to the desired value in each bag, but each pellet will be of e.g.
3043 AN, or MAP, or KCl. Blending plants are the least expensive, requiring only storage,
3044 physical mixing and bagging operations, and have the highest flexibility in terms of
3045 products offered.



3046

3047 **Figure 15: Production routes for P-fertilisers that are derived from mined phosphate rock**
3048 **(DAP: diammonium phosphate; MAP: monoammonium phosphate; TSP: triple**
3049 **superphosphate; SSP: single superphosphate; NPK: Fertiliser containing nitrogen, phosphorus**
3050 **and potassium) (source: European Phosphate Fertilizer Alliance (2017))**
3051

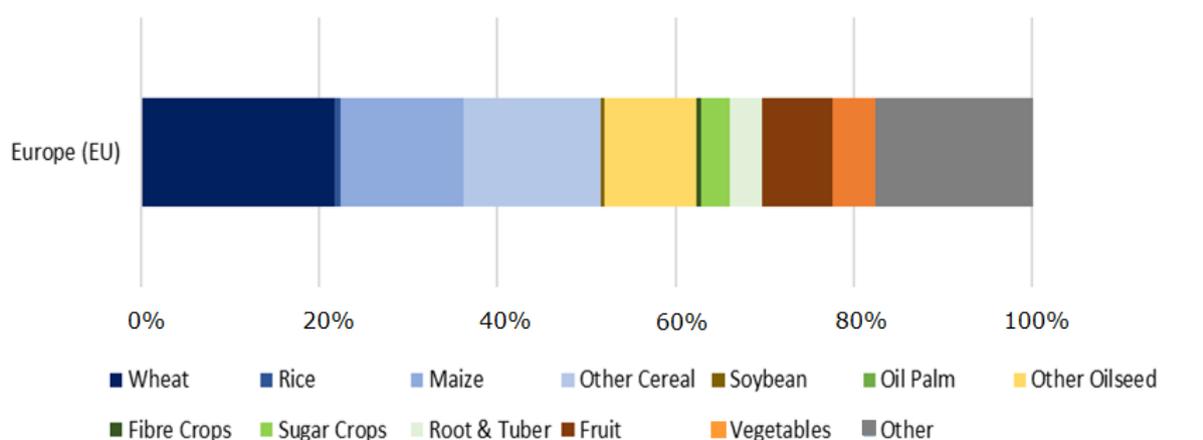
3052 8.1.2 Market drivers for P-fertiliser demand

3053 The main **long-term macro-economic drivers** for P-fertilisers are **population growth**,
3054 changing diets, determining how many people need to be fed, and **per capita income**,
3055 determining how much that population has to spend on food and therefore the quantity and
3056 quality of food they can afford.

3057
3058 In addition to the macro-economic drivers, both annual and regional demand for P-fertilisers
3059 will vary according to the influences of a range of factors, with crop plantings as the most
3060 important one (in turn influenced by crop prices). The price of fertilisers can also have an
3061 influence, as – increasingly - does the weather. Government policy also plays a significant
3062 role in the demand for fertiliser, as can local agricultural practices.

3063
3064 Different crops require differing quantities of N, P and K to produce optimum yields. IFA has
3065 been collecting and monitoring fertiliser use by crop at the global level for a number of years.
3066 In its most recent report (IFA, 2013), a breakdown of P-demand by crop was given for
3067 Europe (Figure 16). Cereals consumed >50% of all P-fertilisers in 2010-11.

3068



3069

3070 **Figure 16: P-fertiliser use by crop (%) in Europe for the year 2010/2011 (Source: IFA)**

3071

3072 **The main driver of the reduction in apparent P-fertiliser consumption in Europe has**
3073 **been the significant change to agricultural policy implemented from 2003.** The most
3074 relevant of these has been the decoupling of subsidies from production, which was agreed in
3075 June 2003, for implementation from May 2005. Prior to 2005 the more farmers produced in
3076 volume terms the more subsidies they received. **Since 2005, the subsidy has been as a**
3077 **single farm payment, which is subject to meeting a number of conditions relating to**
3078 **factors such as environmental compliance and quality, food safety and animal welfare.**
3079 There is discretion across the EU in terms of implementation but over time the reform, by
3080 promoting factors other than production has caused that production and fertiliser use
3081 declined, or at best stabilised, in the period to 2008. For example, maize production in the
3082 EU-28 dropped from 73 Mt in 2004 to 49 Mt in 2007, and wheat dropped from 150 Mt to 121
3083 Mt over the same timeframe. **Since then, as the impact of the revised subsidy faded,**

3084 **production has grown modestly: based on rolling 5-year averages for 2008 and 2015**
3085 **production has grown at 1.04% p.a. through the period.**

3086 The impact of **climate change and the weather** will probably play an increasing role in
3087 affecting annual volumes. Although the full impacts of climate change on the weather are not
3088 yet clear, it does seem that more extreme weather patterns are emerging – bigger storms,
3089 more severe droughts and floods etc (climate variability). The impact of this will be an
3090 increased volatility of demand – if there is a significant risk of losing a crop farmers will
3091 either not apply P, or reduce the amount added to mitigate the risk.

3092 **In conclusion, the main long-term global drivers for phosphate demand will be**
3093 **population growth and the continued economic prosperity of each country. At a**
3094 **regional and national level, and on an annual basis, the mix of crop plantings, crop**
3095 **prices, the weather, government policy and fertiliser prices will all influence how**
3096 **demand develops.**

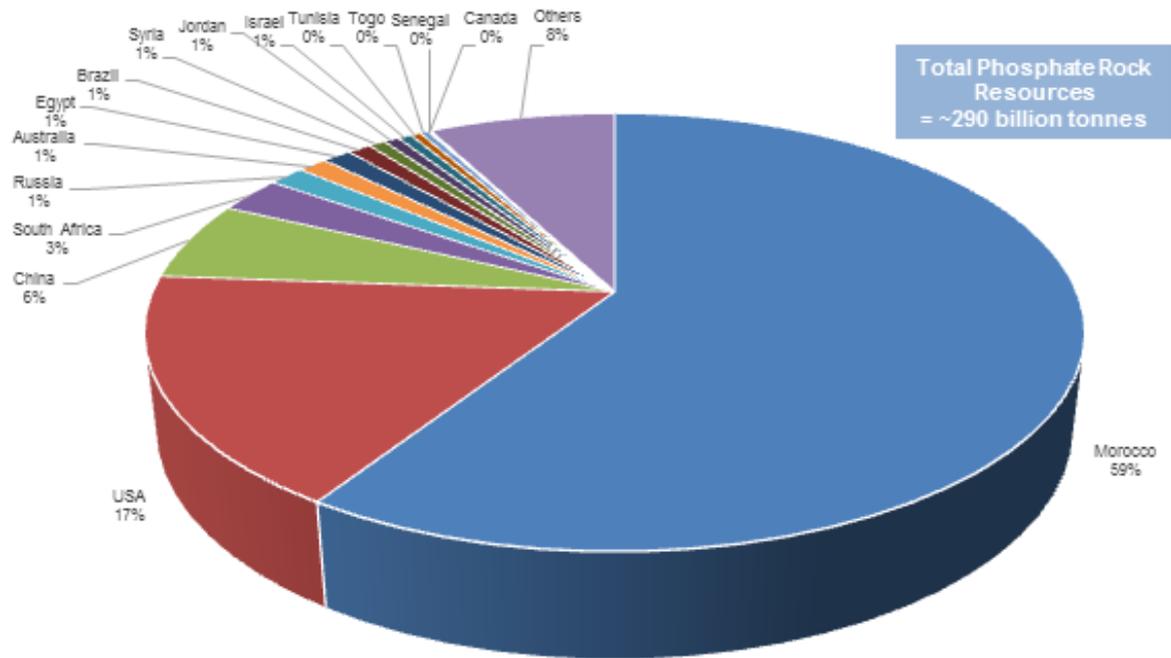
3097

3098 8.1.3 Production and consumption volumes

3099 *8.1.3.1 Raw materials for P-fertiliser production*

3100 The primary raw material for the P-fertiliser industry is **phosphate rock**. Phosphate rocks can
3101 be igneous (volcanic – e.g. the rock deposits in the Kola Peninsula in Russia, at Phalaborwa
3102 in South Africa, and in a number of locations in Brazil amongst others), but most commonly
3103 are sedimentary, being made up from the bones (calcium phosphate) laid down in shallow
3104 seas over millions of years. Most sedimentary rocks contain some phosphate, but economic
3105 deposit of phosphate rock occur where there are one or more seams of rock containing
3106 generally more than 15% P₂O₅, which have uniform texture and composition. Morocco has
3107 the largest proven reserves of phosphate, but the International Fertilizer Association (IFA)
3108 noted that **commercial production of phosphate rock took place in 29 countries in 2015.**
3109 The most important commercial resources are given in Figure 17.

3110



3111

3112 **Figure 17: Global Phosphate Rock Sources (Source: IFDC, 2010)**

3113

3114 Europe has only one active phosphate rock mine, owned and operated by Yara, and located at
 3115 Siilinjärvi in Finland (Davidson and Sheldon, 1986). Most of this rock is used by Yara at its
 3116 manufacturing sites in Finland, or elsewhere in the Nordic region. It therefore follows that
 3117 most of the rock used in Europe is imported from outside the region. There are other
 3118 phosphate resources in Europe, including:

- 3119 • Igneous carbonatite outcrops in Sweden, Norway, Scotland and Spain
- 3120 • Sedimentary deposits in Belgium, France, Germany
- 3121 • Metamorphic deposit in Serbia

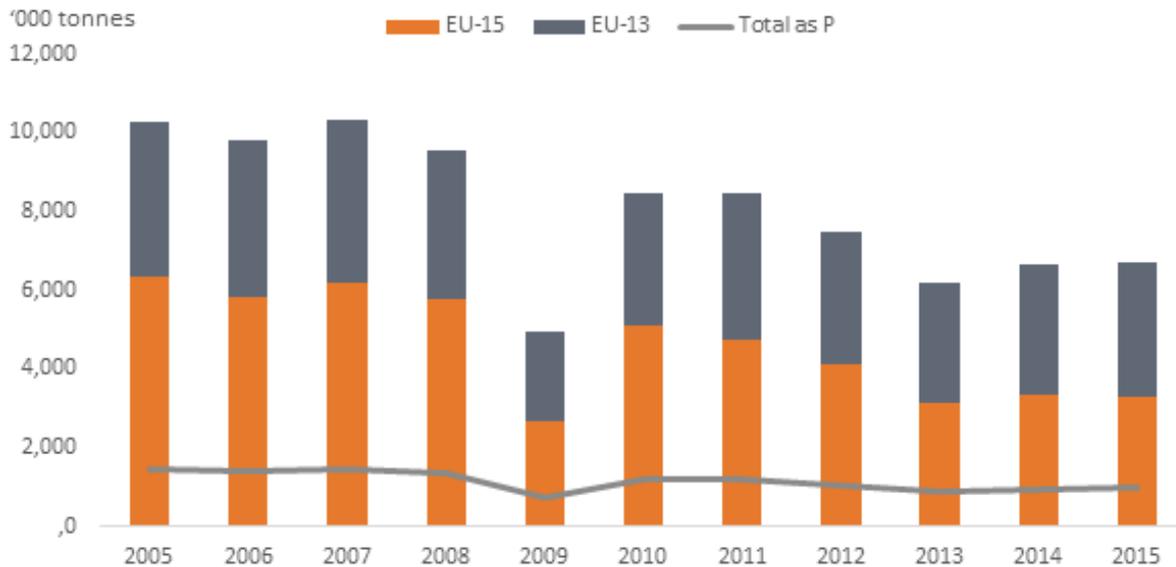
3122 None of these are currently deemed to be commercially viable. Yara has a project to develop
 3123 a second resource in Finland at Sokli, north of the Arctic Circle, but the project is currently
 3124 stalled as there may be alternative long-term sources for the company that are more
 3125 commercially attractive.

3126 **Phosphate rock is thus mined mostly outside of the European Union** and either imported
 3127 into the European Union **as rock**, or further **processed abroad and brought into the**
 3128 **European Union as a semi-product or product**: phosphoric acid, diammonium phosphate
 3129 (DAP), monoammonium phosphate (MAP), triple superphosphate (SSP), single
 3130 superphosphate (SSP). The main phosphate rock importing countries in the EU are Lithuania,
 3131 Poland, Belgium, Bulgaria, Romania and Spain. Most of EU imports come from Morocco
 3132 (1.6 Mt), Russia (1.4 Mt), Algeria (702 kt), Israel (506 kt), and South Africa (429 kt).

3133 **Imports of rock** into Europe have declined from around 9.6 million tonnes to 6.0 million
 3134 tonnes in the 10 years between 2005 and 2015. The phosphate content of the rock imported
 3135 has remained fairly constant at between 31.9% and 32.9% P₂O₅ (13.9% to 14.3% P). Imports
 3136 have declined in both the original EU countries (EU-15) and the more recent accession

3137 countries (EU-13), but much more so in the former than the latter. The compound average
 3138 decline in imports between 2005 and 2015 in the EU-15 is 7.9% p.a., whereas in the EU-13 it
 3139 is a much more modest 1.2% p.a. decline. With only very modest extraction of rock in
 3140 Europe (0.7 Mt phosphate rock from Finland), apparent consumption follows the same
 3141 pattern as imports. For the year 2015, Fertecon estimated that **the total apparent P-**
 3142 **consumption as phosphate rock in the EU-28 equal ~936 kt P** (6.7 Mt material x 0.32 kg
 3143 P_2O_5 / kg phosphate rock x 0.437 kg P/ kg P_2O_5).

3144



3145

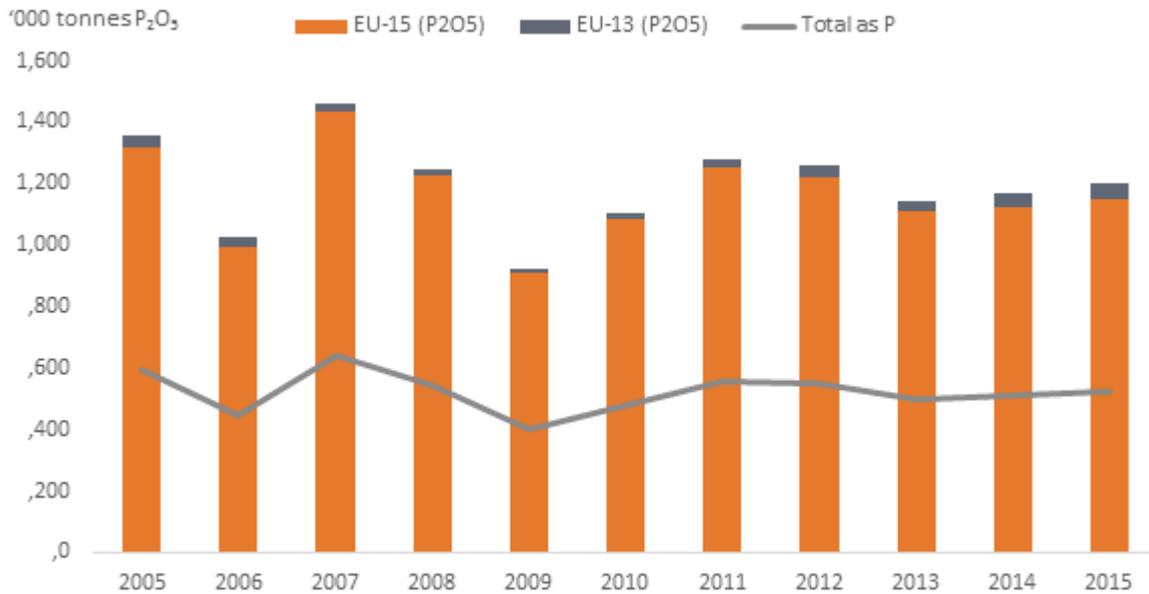
3146 **Figure 18: Phosphate rock apparent consumption for all applications in Europe, 2005 – 2015-**
 3147 **(Sources: IFA, GTIS, Fertecon)**
 3148

3149 Since 2005 apparent phosphate rock **consumption** in the EU-15 countries has declined by
 3150 6.3% p.a., compared with a more modest 1.4% p.a. in the EU-13 countries (Figure 18). Since
 3151 2010 apparent consumption for the EU-13, when seasonal fluctuations are removed, seems
 3152 stable, whereas in the EU-15 countries it has reduced from levels typically above 5.0M
 3153 tonnes product to levels below 3.5M tonnes product (Figure 18).

3154 The other main source of phosphate raw material for Europe is **phosphoric acid**. Acid is
 3155 imported in two main forms, Merchant Grade Acid (MGA, otherwise known as green acid or
 3156 fertiliser acid), which is an impure acid containing around 54% P_2O_5 , and purified phosphoric
 3157 acid (PPA, otherwise known as white acid), typically containing around 61% P_2O_5 . MGA is
 3158 used as a feedstock for fertiliser and animal feed products, purified acid is used for industrial
 3159 applications including some speciality fertilisers (frequently, but not exclusively fully soluble
 3160 products). **For the year 2015, it is estimated that the total P-imports as phosphoric acid**
 3161 **in the EU-28 equal ~ 524 kt P** (Figure 19). The EU-15 accounts for over 95% of all
 3162 phosphoric acid imports in the EU (Figure 19). This might overstate reality, depending on the
 3163 accuracy of data on re-exports from key import-ports in e.g. the Netherlands and Belgium,
 3164 but there is no doubt at all that the EU-15 will account for the majority of the use of imports.

3165 Imports to the EU-15 have declined by 1.3% p.a. in the 2005 – 2015 timeframe, whereas
 3166 imports have grown at 1.8% p.a. in the EU-13 region.

3167



3168

3169 **Figure 19: Imports of phosphoric acid into Europe by region (Source: GTIS, IFA)**

3170

3171 *8.1.3.2 Finished P-fertilisers*

3172 Eurostat publishes two data sets on inorganic fertilisers use. The first one is collected from
 3173 Member States and is an estimate of the N and P use in agriculture. However, data on
 3174 fertiliser consumption is available in many countries from country specific data sources
 3175 (surveys, trade/production statistics) that are not always trustworthy. **As indicated by**
 3176 **Eurostat itself, the quality of data cannot be sufficiently verified** due to different data
 3177 sources used (farmer surveys vs trade/production statistics) and inherent problems of data
 3178 sources used (for instance inclusion of non-agricultural use in statistics based on trade and
 3179 production). This involves significant limitations as, for instance, the reliability and accuracy
 3180 of farmer surveys depend amongst others on the sampling design and size.

3181

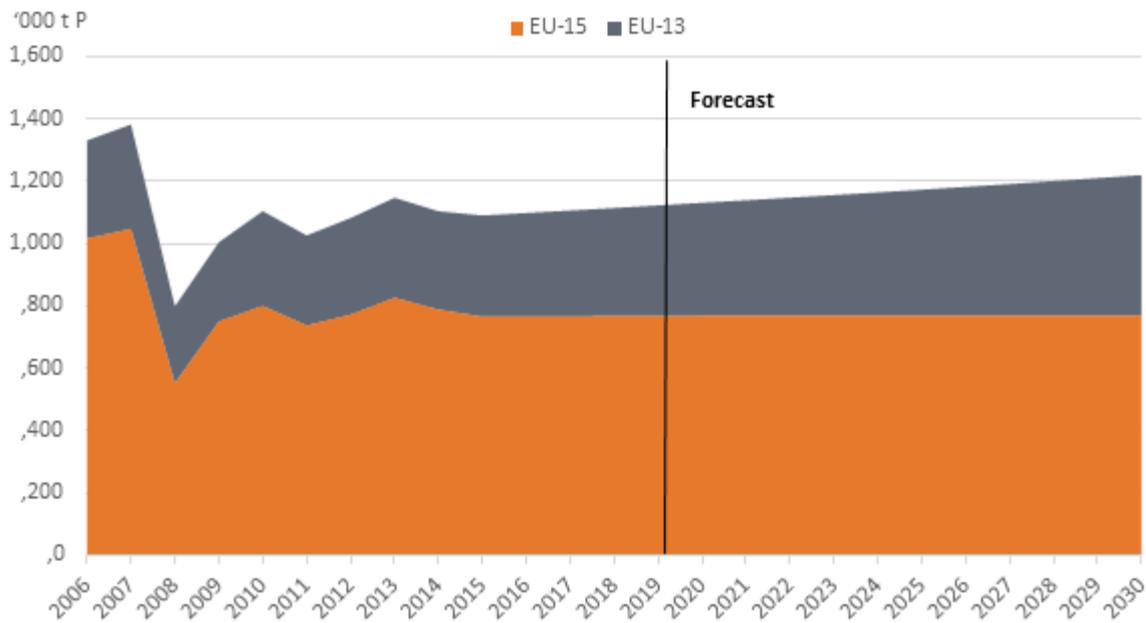
3182 The other data set is estimated consumption based on the sales of mineral fertiliser in the EU-
 3183 28 from **Fertilizers Europe**. The figures estimated by the trade association Fertilizers Europe
 3184 based on sales of mineral fertiliser mostly correspond with the estimates of N and P use
 3185 reported by countries although they cannot be directly compared due to methodological
 3186 differences. This is a harmonized data source. Data are available at NUTS0 for EU-27 (i.e.
 3187 does not include Croatia). Data from Fertilizers Europe relate to crop years (t-1/t) which are
 3188 reported under year t-1. These data have been used in this assessment, also because they are
 3189 in between the Member State data documented by Eurostat and the FAO.

3190

3191 **Fertilizers Europe assessed the apparent P-consumption for fertilisers in the EU-28 at**
 3192 **1090 kt P in 2015** (Figure 20). Eurostat estimated the total P-consumption as mineral

3193 fertilisers at 1133 kt P for the year 2015, whereas FAOSTAT documents 1070 kt P for the
 3194 EU-28 in 2015. The data from Fertilizers Europe indicate that mineral P-fertiliser
 3195 consumption was larger in the EU-13 (70%, 765 kt P yr⁻¹) than in the EU-13 (30%, 325 P yr⁻¹) (Figure 20).
 3196
 3197

3198 **Looking forward, Fertecon forecasts phosphate consumption for fertilisers to grow**
 3199 **across the EU-28 at a CAGR (Compound Annual Growth Rate) of 0.8% p.a. for the**
 3200 **next decade.** Growth in the EU-15 is stable within any reasonable margin of error (0.09%
 3201 p.a.). Fertecon, however, forecasts a growth in the EU-13 countries at a CAGR of 2.2%
 3202 (Figure 20). Future estimates on mineral P-fertiliser consumption were obtained by projecting
 3203 these CAPR growth rates, resulting in a 2030 estimate of 1220 kt P yr⁻¹. The EU-13 still had a
 3204 dominant share of the total mineral P-consumption (63%; 769 kt P yr⁻¹), but the contribution
 3205 of the EU-13 increased to a total value of 37% (450 kt P yr⁻¹).
 3206

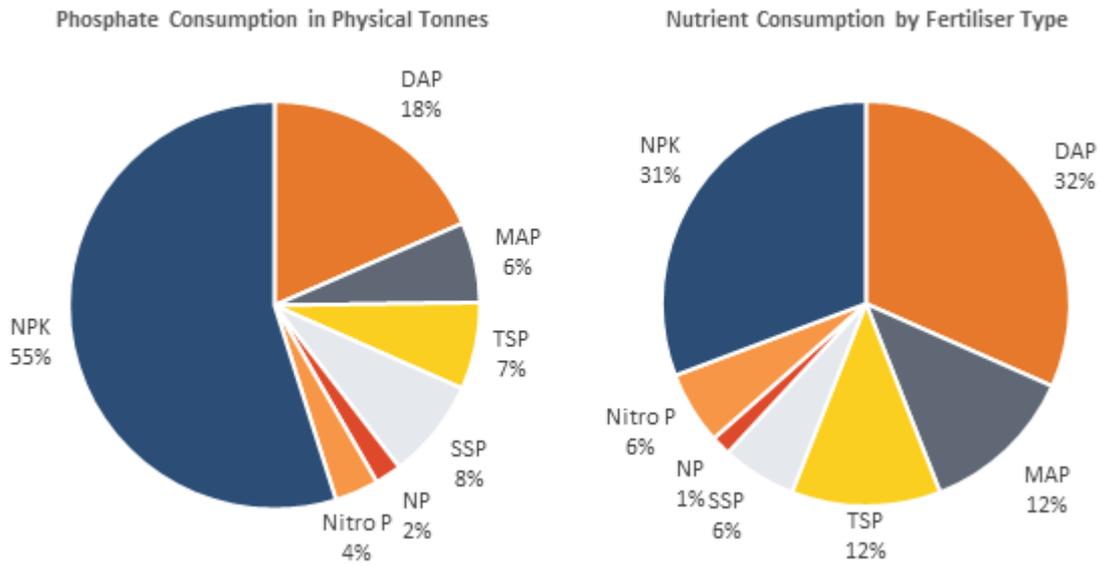


3207
 3208 **Figure 20: Apparent Consumption of mineral P-fertiliser in the EU-28 (kt P yr⁻¹) (Source:**
 3209 **Fertecon)**
 3210

3211 Although traditionally P-fertiliser and NPK fertiliser producers purchase phosphate rock to
 3212 produce fertilisers within Europe, in recent years some of the producers have – for numerous
 3213 reasons (price, environmental or others) – **suspended or abandoned purchases of**
 3214 **phosphate rock and have chosen instead to purchase phosphoric acid.** Some of them
 3215 have even temporarily decided to move even further downstream and purchase MAP or DAP.
 3216 instead (European Phosphate Fertilizer Alliance, 2017).

3217 The apparent consumption of phosphate in the EU-15 both in terms of the physical tonnes of
 3218 products containing P, and the total P-content delivered through those products is given in
 3219 Figure 21. The analysis shows that in terms of product types, NPKs accounted for 55% of P-
 3220 containing tonnes consumed, followed by DAP (18%) and SSP (8%) (Figure 21). In terms of

3221 **actual P delivered** however, because NPKs contain less P than as MAP, DAP or TSP, the
 3222 proportions change. **DAP has the largest share at 32%, followed by NPKs at 31%, and**
 3223 **MAP with 12%** (Figure 21).
 3224



3225
 3226 **Figure 21: Apparent consumption of P-fertilisers in the EU-28 for the year 2015. The left Figure**
 3227 **indicates the actual tonnes of material; the right Figure indicates the same data expressed on a**
 3228 **P-basis (Source: Fertecon)**
 3229

3230 The data from Fertilizers Europe indicate that France is the largest consumer of phosphates
 3231 for fertilisers, with a share assessed at 17% of the EU-28 in 2015. Spain is the second largest
 3232 market (15%) followed by Poland (13%). The top 7 markets accounted for just over 76% of
 3233 apparent consumption of phosphate for fertilisers, with the balance spread over the remaining
 3234 EU countries (Figure 22).
 3235

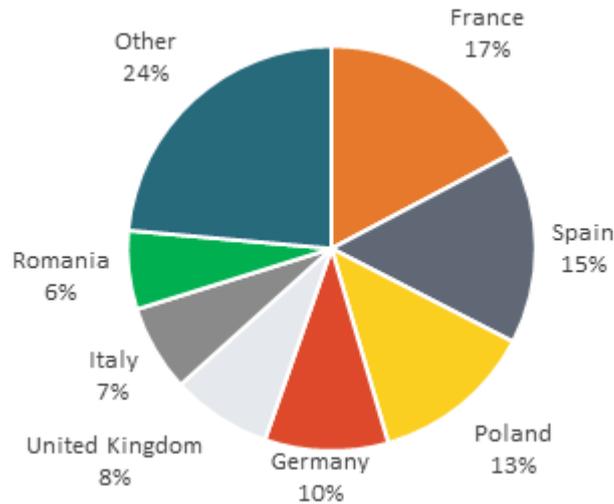


Figure 22: EU-28 Top 10 markets for apparent consumption of mineral phosphate fertilisers for the year 2015 (Source: Fertilizers Europe)

Box 2: Production of DAP, MAP, TSP, SSP and NPK in the EU (AEEP, 2017; Fertecon):

- Diammonium phosphate (DAP, $(\text{NH}_4)_2\text{HPO}_4$):** DAP is typically 18-46-0 (i.e. contains 18% N, 46% P_2O_5 and 0% K_2O). It was one of the first fertilisers to have a standardised content, which in part explains why it is the largest selling phosphate fertiliser. Annual production of DAP in the EU-28 is just under 1.0 Mt or 200 kt P, with Lithuania by far the largest producer, followed by Poland, Spain, and Belgium.
- Monoammonium phosphate (MAP, $\text{NH}_4\text{H}_2\text{PO}_4$):** MAP can be between 10-50-0 and 11-55-0. Annual production of MAP in the EU-28 production is a modest 78 kt (18 kt P), with Belgium, Poland, Bulgaria and Spain as the main producers.
- Single Superphosphate (SSP; $\text{Ca}(\text{H}_2\text{PO}_4)_2 + \text{CaSO}_4$):** SSP is typically between 0-16-0 and 0-22-0. Annual production of SSP in the EU-28 accounts for just over 1.0 Mt or 88 kt P. No information is available on imports/exports.
- Triple Superphosphate (TSP; $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$):** TSP is the highest analysis straight phosphate fertiliser, typically ranging between 0-44-0 and 0-48-0. Annual production of TSP in the EU-28 accounts for just over 250 kt or 53 kt P, mostly in Bulgaria.
- NPK Fertilisers:** No direct data are available on the total production of NPK fertilisers in Europe.

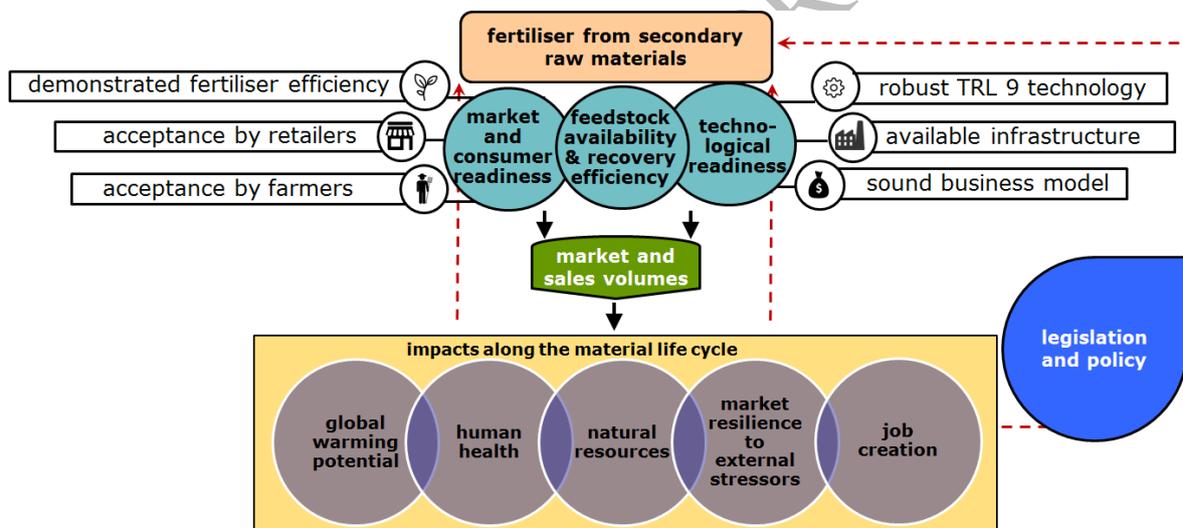
8.2 Market outlook for P fertilisers derived from STRUBIAS materials for the year 2030

8.2.1 General considerations

3263 **The market potential of STRUBIAS materials is based on estimates of plant-available P.**
 3264 The agronomic efficiency of fertilisers containing STRUBIAS materials is expressed relative
 3265 to mineral P-fertilisers based on the so-called "relative agronomic efficiency" (see section 5).
 3266 A relative agronomic efficiency value below 100% indicates that that the fertiliser derived
 3267 from STRUBIAS materials is a less effective plant P-source than a synthetic P-fertiliser
 3268 derived from mined phosphate rock, and vice versa.

3269
 3270 The market for P-fertilisers derived from STRUBIAS materials is dependent on the
 3271 **technological readiness** and potential production limitations of the production processes,
 3272 **market and consumer readiness**, and the **impacts** along the STRUBIAS material life cycle
 3273 (Figure 23). Legislative and policy impacts due to beneficial impacts of STRUBIAS
 3274 materials relative to alternative fertilising products that are available on the internal market
 3275 are considered. As matter of fact, given that the production cost for STRUBIAS might be
 3276 higher than for mined fertilising products (Egle et al., 2016), legislative aspects and policies
 3277 may prove to be important drivers for STRUBIAS materials.

3278
 3279



3280
 3281 **Figure 23: Schematic overview of the market drivers for P-fertilisers derived from secondary**
 3282 **raw materials**
 3283

3284 The market for STRUBIAS materials will not only depend on the nutrient recovery rules as
 3285 laid down in the fertiliser product legislation, but also on national and EU legislation related
 3286 to specific **eligible input materials** (e.g. Directive 2008/98/EC on waste and by-products,
 3287 Regulation (EC) No 1069/2009 as regards animal by-products, Regulation (EC) 86/278 as
 3288 regards sewage sludge, etc.), **nutrient use and management** in crop and livestock
 3289 production, and **prevention and reduction of water pollution** (Buckwell and Nadeu, 2016).
 3290 Moreover, links exist with the **bioeconomy initiatives and related legislation**, and more
 3291 specifically Directive 2009/28/EC on the promotion of the use of energy from renewable
 3292 sources. The existing legal framework and policy incentives vary considerable as a function
 3293 of eligible input materials. When relevant, the relation of existing EU legislation to
 3294 STRUBIAS market aspects will be discussed for the eligible materials. **In case STRUBIAS**

3295 **materials are associated to a positive impact on the environment, human health, or the**
3296 **circular economy in general, positive feedback loops due to legislative and policy**
3297 **initiatives could possibly further stimulate the market** (see section 8.2.10.2).

3298 The sections 8.2.4 - 8.2.8 discuss market estimates under the anticipatable EU and national
3299 legislation for all process pathways of high technological readiness level (TRL 7-9). A broad
3300 spectrum of new STRUBIAS production processes are emerging and developing, some of
3301 them being present at TRL 6 level ("System/subsystem model or prototype demonstration in
3302 a relevant environment"). **It is, nonetheless, challenging to predict a 2030 market for**
3303 **production pathways that might still face technological and market failures during the**
3304 **remaining TRL stages ahead.** Therefore, the market assessment TRL 6 processes are
3305 discussed together with possible legislative drivers in section 8.2.10.2.

3306

3307 8.2.2 Market and consumer readiness

3308 8.2.2.1 *Conventional agriculture*

3309 STRUBIAS materials are used to produce a variety of fertilising products (see section 4). On
3310 the one hand, **STRUBIAS materials can be used for the production of traditional P-**
3311 **fertilisers of well-known chemical composition such as DAP, MAP, TSP, SSP, etc.** On the
3312 other hand, STRUBIAS production processes may expand the variety of P-fertilising
3313 products on the market by producing P-fertilising products **of a different chemical**
3314 **composition.** Several of these "new" P-fertilisers are marketed as "slow-release" or
3315 "controlled-release" because the P is not water-soluble. Development of new fertiliser
3316 products requires determining key properties of the materials that affect storage and
3317 spreading, soil behaviour, and agronomic efficiency. **Knowledge of these properties is of**
3318 **prime importance to increase market and consumer readiness for new fertilisers** (Antille
3319 et al., 2013).

3320

3321 STRUBIAS materials should preferentially be **available in a physical form that enables**
3322 **their homogeneous distribution across the agricultural field and their application using**
3323 **conventional application equipment.** With the increased need and readiness of the sector to
3324 increase nutrient-use efficiency, it is important that the fertiliser characteristics enable the
3325 accurate distribution of fertilisers within the field. At the same time, there is a strong
3326 preference to use existing machineries that apply fertilisers in a time and energy-efficient
3327 manner, for which reason the physical form of the fertilisers should be compatible with
3328 existing machineries. This implies, for instance, that fertilisers that will be broadcasted
3329 should preferentially comply with physical characteristics such as bulk density, grain size
3330 distribution, sphericity, hardness, brittleness, dust rate, resistance to humidity, resistance to
3331 weight increase, etc. (Antille et al., 2013). Fertiliser materials which have moderately high
3332 crushing strength can better resist handling, storage, and spreading without significant
3333 shattering, dust formation, or caking. Density properties are related to the volume needed for
3334 storage and transport, and are required to calibrate fertiliser spreading equipment. Particle
3335 size and size distribution affect uniformity of distribution during field application, and it is
3336 well documented that uneven spreading of fertilisers can increase nutrient losses to the

3337 environment, reduce fertiliser use efficiency and crop profit margins. Alternatively, materials
3338 could be applied using lime spreaders that homogeneously distribute fertiliser materials on
3339 the field, albeit in a more labour-intensive manner.

3340
3341 Fertiliser blending companies could incorporate STRUBIAS materials as part of a physical or
3342 chemical blend together with traditional mineral fertilisers on condition that they meet certain
3343 characteristics (e.g. with respect to material purity and granulometry (Formisani, 2003)).
3344 Also, certain combinations of molecules should be avoided due to possibly occurring
3345 chemical reactions in the granulator that cause nutrient loss or reduce the water solubility of
3346 specific elements in the blend. Certain fertiliser companies are in the process of **testing**
3347 **and/or partially including struvite and poultry litter as part of compound mineral P-**
3348 **fertilisers**. ICL Fertilisers has successfully tested partial struvite incorporation in their
3349 compounding process (20% of the total P in the blend). Given that the P in good-quality
3350 recovered phosphate salts is already in plant-available form, there is no need for acidulation;
3351 ICL tests indicated that in quantities <20%, recovered phosphate salts can be placed directly
3352 in a granulator with acidulated phosphate rocks (Six et al., 2014). In such a process, struvite
3353 is physically mixed with phosphorus fertilisers and possibly with N, K and other nutrient
3354 sources. It is not chemically converted. Struvite will in this case be used as a P, N and Mg
3355 source and will require identical application machinery as for traditional P-fertilisers. Some
3356 fertiliser blending companies formulate poultry litter ashes as powder with KCl or TSP.

3357
3358 The above assessment indicated that a market entry for recovered P-fertilisers would only be
3359 based on **proven agronomic benefits and equal fertiliser efficiencies relative to**
3360 **traditional P-fertilisers expressed on a monetary basis**. Such proof would not be available
3361 until **comprehensive agronomic testing** under different climate and soil conditions are
3362 complete, which will require a minimum of 3 or 4 years of field trials, and probably more.
3363 With the exception of struvite and poultry litter ashes, such assessments have not yet started
3364 for most recovered products that have a different chemical composition than those products
3365 currently dominating the market (DAP, MAP, TSP, SSP, nitrophosphate, etc.). There is an
3366 increased acceptance for controlled release fertilisers within the European agricultural sector,
3367 but the agronomic value of the marketed product should be extensively demonstrated before a
3368 market breakthrough for new fertilising materials can be expected.

3369
3370 In conventional European agriculture, the P-fertilisers MAP and DAP (with a P₂O₅-content of
3371 48-61% and 46%, respectively) or physical blends (NPK) make up more than 75% of the
3372 total mineral P-fertilisers applied, expressed on a P-basis (see section 8.1.3.2). The straight P-
3373 fertiliser TSP (45% P₂O₅) and SSP (16-20% P₂O₅) only make up 18% of the total share of all
3374 P-fertilisers, expressed on a P-basis (see section 8.1.3.2). A major reason for this observation
3375 is the ease and efficiency of fertiliser application and distribution logistics. **The nutrient**
3376 **content of the fertiliser directly impacts upon the logistic cost for the transport,**
3377 **distribution and application of fertilisers, a cost which exceeds in some cases the cost of**
3378 **fertiliser purchase**. Therefore, nutrient-dense fertilisers will provide clear benefits for the
3379 downstream transport, distribution, and application by retailers and farmers.

3380

3381 Some recovered fertiliser products could also enter the market in **specific segments that**
3382 **deliver the highest margins**. Struvite and poultry litter ashes are, for instance, currently
3383 already sold in specific niche segments of the fertiliser market. In the early stages of market
3384 development, it may lead fertiliser producers to choose physical and chemical forms that are
3385 specifically adapted to these markets. The STRUBIAS application potential in niche markets
3386 includes for instance use in **growing media** for greenhouse farming or the fertilisation of
3387 **grasslands** where some STRUBIAS materials show a high potential.

3388
3389 Assuming a similar price setting as for traditional P-fertilisers, it is concluded that fertilisers
3390 derived from STRUBIAS materials should meet numerous conditions in order to provide a
3391 substantial spot-on alternative for synthetic and mined P-fertilisers in conventional farming.
3392 The fertiliser end-product should preferentially be presented in a **physical form that enables**
3393 **its efficient application** and its **agronomic efficiency should be well-demonstrated**.
3394 Additionally, it is advisable that P-fertilisers derived from STRUBIAS materials have
3395 characteristics that enable the use in fertiliser blends together with other plant macronutrients
3396 to increase nutrient-density. **Therefore, STRUBIAS materials contained in compound P-**
3397 **fertilisers of chemical composition that are already available on the market and slow-**
3398 **release fertilisers that are well-advanced in the process of agronomic efficiency testing**
3399 **and are compatible for blending are associated to the highest degree of market and**
3400 **consumer readiness, at least for conventional agriculture**. Phosphorous fertilisers that do
3401 not meet these conditions may possibly be relevant for specialised market niches or be traded
3402 at a lower price.

3404 8.2.2.2 *Organic farming*

3405 Depending on the input materials and process pathways employed, certain STRUBIAS
3406 materials could be used as fertilisers in organic farming. Agricultural practices, including
3407 fertiliser management, are regulated under the existing legislation (**Council Regulation (EC)**
3408 **No 834/2007 on organic production and labelling of organic products**). The EU organic
3409 farming sector mainly uses organic fertilising materials, but under specific circumstances also
3410 natural or naturally-derived substances and low-solubility mineral fertilisers can be applied.
3411 **Synthetic resources and inputs may only be permissible if there are no suitable**
3412 **alternatives**. Such products, which must be scrutinised by the Commission and EU countries
3413 (the Expert Group for Technical Advice on Organic Production – EGTOP, see below) before
3414 authorisation, are listed in the annexes to the implementing regulation (Commission
3415 Regulation (EC) No. 889/2008).

3416
3417 **The manufacturing of many STRUBIAS fertilisers from secondary raw materials is in**
3418 **line with the objectives, criteria and principles of organic farming and the responsible**
3419 **use of natural resources**. Given the limited availability of concentrated P-fertilisers that
3420 comply with the principles of organic farming, P-fertilisers derived from STRUBIAS
3421 materials could potentially fulfil an important role as fertilising material for the sector. P-
3422 fertilisers derived from STRUBIAS materials could provide an alternative for meat and bone
3423 meal, meat and bone meal ashes and low concentrated P-fertilising products such as manure

3424 and compost that are currently the major P-sources in organic farming (Nelson and Janke,
3425 2007). Because of the low N:P ratios of many organic inputs, organic farmers often over-
3426 fertilise for P while trying to match crop N requirements; evidence on the potential uptake of
3427 STRUBIAS materials remain indeterminate, except in organic systems that rely on biological
3428 N fixation for N inputs (Seufert and Ramankutty, 2017). In 2015, the percentage of the total
3429 utilised agricultural area within the EU for organic farming was 6.2%, of which 42% was
3430 planted with arable crops. **The expanding organic farming sector could, however, become**
3431 **a more significant agricultural market in the near future.** The Common Agricultural
3432 Policy (CAP) (2014-2020) recognizes the role of organic farming in responding to consumer
3433 demand for more environmentally friendly farming practices: under the first pillar organic
3434 farms will benefit from the green direct payment without fulfilling any further obligations
3435 because of their overall significant contribution to environmental objectives.

3436
3437 The EU's "**Expert Group for Technical Advice on Organic Production**" (EGTOP) has
3438 evaluated **positively two dossiers** proposing authorisation of recycled phosphate products as
3439 fertilisers in organic agriculture (under EU Organic Farming Regulation 889/2008). The
3440 dossier for struvite was submitted by the UK in 2014 and concerns struvite (magnesium
3441 ammonium phosphate) recovered in sewage works or from animal waste processing. The
3442 dossier for calcined phosphates was submitted by Austria in 2011 and concerns recovery
3443 from ashes of sewage sludge, meat and bone meal, or other biomass ash. **The committee**
3444 **concludes that for Ostara Pearl struvite (the submitted dossier) there is no hygiene risk**
3445 **(organic pollutants or pathogens), but that this is not proven for other struvite**
3446 **production methods and struvite-like end materials.** EGTOP concluded that struvite
3447 recovery is conform to environmental objectives (reduces N and P losses to surface waters,
3448 recycles nutrients, reduces consumption of non-renewable P resources) and that struvite
3449 should be authorised for organic farming "**provided that the method of production ensures**
3450 **hygienic and pollutant safety**". For calcined phosphates, the committee also concludes that
3451 recovery from ashes is conform to environmental objectives (but with some concerns about
3452 energy consumption) and that calcined phosphates should be authorised for organic farming
3453 **subject to being recovered from sewage sludge incineration ash and that heavy metal**
3454 **content should be limited.** The EGTOP also concluded that these two products cannot be
3455 authorised under the Organic Farming Regulation until they are authorised under the EU
3456 Fertilisers Regulation. **Properly formulated nutrient recovery rules integrated into the**
3457 **revised Fertiliser Regulation could address the above considerations from the EGTOP**
3458 **and hence facilitate the market entry of STRUBIAS materials into the organic farming**
3459 **market.**

3460
3461 It should be noted, however, that STRUBIAS materials for organic farming are most likely to
3462 replace currently used (organic) P-fertilising materials as the use of synthetic and mined P-
3463 fertilisers is negligible in this agricultural sector. Regardless of their volumes used in organic
3464 farming, **the use of STRUBIAS materials as P-sources in organic farming is unlikely to**
3465 **contribute significantly to the substitution of synthetic and mined P-fertilisers** unless a
3466 significant expansion of organic farming occurs prior to the year 2030 at the expense of
3467 traditional farming.

3468

3469 8.2.3 Technological readiness level and potential production limitations

3470 Due to the combination of diverse input materials and output materials that can be produced,
3471 STRUBIAS production processes span a broad range of technological readiness levels. For
3472 the assessment of the market outlook for P-fertilisers derived from STRUBIAS materials for
3473 the year 2030, only STRUBIAS production processes of **technological readiness levels**
3474 **(TRLs) 6-9 are considered:**

- 3475 • TRL 6 – technology demonstrated in relevant environment (industrially relevant
3476 environment in the case of key enabling technologies);
- 3477 • TRL 7 – system prototype demonstration in operational environment;
- 3478 • TRL 8 – system complete and qualified;
- 3479 • TRL 9 – actual system proven in operational environment (competitive manufacturing
3480 in the case of key enabling technologies; or in space).

3481

3482 TRL 6 processes are covered in section 8.2.10.2 whereas TRL 7-9 processes are split up as a
3483 function of eligible input material (see section 8.2.4 - 8.2.8).

3484 The underlying justification for excluding TRL 1-5 processes is the unlikelihood of
3485 technologies of a lower technological readiness level to

- 3486 • surpass TRLs 6-9;
- 3487 • comply with administrative arrangements (e.g. obtain waste treatment permit,
3488 REACH registration of CE fertilising product containing STRUBIAS materials,
3489 arrangements with downstream distributors and retailers, etc.);
- 3490 • build the necessary infrastructure; and
- 3491 • perform extensive product testing on agronomic efficiency.

3492 in order to ensure market and consumer confidence (see section 8.2.2) prior to the year 2030.
3493 Although TRL 1-5 STRUBIAS materials are not covered in this section, the possibility of
3494 such emerging process pathways to contribute to the substitution effect for mined and
3495 synthetic P-fertilisers in the mid- to long-term is not excluded.

3496 An additional point that should be taken into consideration to derive the substitution potential
3497 for the year 2030 is the **availability of infrastructure** required to produce STRUBIAS
3498 materials. STRUBIAS production processes often include different phases and specific
3499 configurations within the production process: struvite can be precipitated in wastewater
3500 treatment plants that use biological nutrient removal techniques, K-struvite can be
3501 precipitated from manures after anaerobic digestion, DAP can be produced from mono-
3502 incinerated sewage sludge ashes, etc. Given that the total production cost of STRUBIAS
3503 materials from some input materials is higher than for P-fertilisers derived from phosphate
3504 rock, the substitution potential will be partially dependent on the extent of existing pre-
3505 treatment processes for primary input materials. Often, such **pre-treatment has other**
3506 **objectives than the recovery of nutrients:** energy recovery from manure, steel products
3507 from ores, etc. An additional aspect related to infrastructure that is especially relevant to
3508 consider for ash-based materials is the **configuration of the incinerator** (mono- versus co-

3509 incineration). This choice has a large impact on the suitable further use of the ashes from
3510 sewage sludge and meat and bone meal for nutrient recovery. It is preferable that P-rich input
3511 materials are mono-incinerated because co-incinerated materials are less suitable for P-
3512 recovery due to P-dilution. Even in Member States such as Germany and the Netherlands that
3513 incinerate a dominant share of their sewage sludge, mono-incinerators currently only process
3514 50% or less of the current volumes (STOWA, 2011; Wiechmann et al., 2013). In the interest
3515 of promoting more efficient recycling of the P in sewage sludge, the mono-incineration
3516 capacity should therefore be increased in the EU.

3517 A major challenge also lies in increasing the production volumes of P-fertilisers derived from
3518 secondary raw materials. With the exception of struvite producing plants, EcoPhos and 3R
3519 agrocarbon (animal bone biochar), **P-recovery facilities are at present still piloting or**
3520 **producing minor P-fertiliser volumes compared to the apparent fertiliser P-**
3521 **consumption in Europe.** Other promising technologies, such as RecoPhos and Budenheim,
3522 will start to build full-scale installations in Europe, of which the first will most likely be
3523 operational in 2018. It should be evaluated to what extent current P-fertiliser production
3524 processes through the acidulation route could be adapted to use other P-sources than
3525 phosphate rock (for instance P-rich ashes). Leading P-fertiliser companies aim at decreasing
3526 their reliance on phosphate rock, but further technical process refinements may be required.
3527 Therefore, the recovered P-fertiliser volumes will only gradually become more abundant in
3528 the coming years. ICL Fertilisers has, for instance, expressed the ambition of substituting 25
3529 kt of P yr⁻¹ by the year 2025.

3530 In the following sections, the market potential for STRUBIAS materials derived from
3531 different input materials will be discussed, considering possible limitations on feedstock, P-
3532 recovery efficiency and available infrastructure.

3533

3534 8.2.4 STRUBIAS materials from crop residues, manure, and bio-waste

3535 8.2.4.1 Introduction

3536 In Europe, most **agricultural crop residues arise** on farms in the form of straw, maize
3537 stover, residues from sugar beet, oilseeds, grass cuttings, and pruning and cutting materials
3538 from permanent crops, and in the crop processing sector in the form of olive pits, seed husks,
3539 nut shells. By far the largest source of crop residues is the straw and stover from grain crops
3540 (wheat, barley and maize) (Kretschmer et al., 2013). There are essentially two overarching
3541 challenges to mobilising crop residues (Kretschmer et al., 2013). **Transport costs are high**
3542 because the residues are highly dispersed and have high bulk volumes and low value. This
3543 limits the range over which they can economically be collected for processing and makes it
3544 important that processing plants are optimally located. This requires appropriate investment
3545 in machinery and equipment, which may be beyond individual farmers' reach and necessitates
3546 cooperative action or specialised contractors. Harvesting costs can also be high in relation to
3547 the value of the material. Secondly, **many crop residues have existing uses and established**
3548 **practices, particularly for recycling organic materials back to the soil.** There is poor
3549 awareness of sustainable extraction rates in relation to local conditions. There are therefore

3550 real risks that overextraction could cause detrimental reduction of soil organic matter with
3551 knock-on effects for wider soil functionality, soil biodiversity and erosion risk. Together
3552 these issues into account, the realistic potential derived from the technical-sustainable
3553 potential for agricultural crop residues – excluding grasslands - to contribute to renewable
3554 energy production has been estimated at 75 million tonnes per year in the EU-28, with a
3555 dominant contribution of the cereals wheat, maize and barley (Iqbal et al., 2016). The total P
3556 content in those crop residues would be around 110 kt P yr⁻¹ (see section 3.2).

3557 Much of the off-land technology for dealing with biomass is well understood and long
3558 established. Generally, the biomass based raw materials will require some physical **pre-**
3559 **treatment**, for example to separate components, dry, chop, and pelletise. Then, the
3560 processing will either follow a **biochemical pathway** (based on digestion, transesterification,
3561 or fractionation, the latter also serving as a type of pre-treatment) or a **thermochemical**
3562 **process** (based on hydrogenation, gasification or pyrolysis). The review of a wide range of
3563 life cycle assessments (LCA) for different treatments for crop residues shows the superiority
3564 of the anaerobic digestion pathway over other pathways for energy recovery and other bio-
3565 based applications from crop residues (Kretschmer et al., 2013). Thermochemical conversion
3566 technologies are less suitable for the direct processing of crop residues, characterised by
3567 relatively high moisture content.

3568
3569 Manure is defined as a Category 2 Animal By-product material according to Regulation (EC)
3570 No 1069/2009. Pursuant to this Regulation, **it can be applied to land without processing**.
3571 Most European countries have similar supplementary regulations regarding livestock farming
3572 including (i) licensing required for housing animals, (ii) storage of manures and slurries to
3573 enable a better agronomic utilization and (iii) prohibited periods for land spreading (usually
3574 the winter months of November to February). There are, however, differences between
3575 countries - and even between regions of the same country - as a consequence of the local
3576 situations and locally defined Nitrate Vulnerable Zones. A common pollution concern is
3577 nitrate contamination of water, but in most countries there are other pollution issues including
3578 ammonia emission (in the Netherlands) and odour nuisance (in the UK and Greece).

3579 In 2010, about **7.8% of the livestock manure production in the EU was processed, equal**
3580 **to a total manure volume of 108 million tonnes/year, and containing 556 kt N and 139 kt**
3581 **P** (Foget et al., 2011; Flotats et al., 2013). At least **45 different manure treatment**
3582 **technologies** are available (Foget et al., 2011). The largest levels of livestock manure
3583 processing were recorded in Italy, Greece and Germany, with 36.8%, 34.6% and 14.8% of the
3584 manure production being processed, respectively. The **objectives** for manure processing
3585 include **increasing the handling and management** for storage and transport of nutrients
3586 (viscosity, greenhouse gas emissions, storage of reduced volumes, etc.), the **selective**
3587 **removal of nutrients** (especially N), and **incentives received for renewable energy**
3588 **production** (biogas).

3589 **A clear tendency identified is that anaerobic digestion is the “door-opener” for the**
3590 **introduction of nutrient recovery technologies for cattle and pig manure of high**
3591 **moisture content (Foget et al., 2011)**. Several EU Member States have no other type of
3592 manure processing than anaerobic digestion (Foget et al., 2011). The reason for this is that
3593 most of the manure nutrient processing technologies are complementary to anaerobic

3594 digestion, either as pre-treatment technologies that can enhance the biogas production, or as
3595 post-treatments, which can help to convert the digestate into products with envisaged
3596 properties (Foget et al., 2011). Solid manure fractions, such as poultry manure, can also be
3597 used for direct incineration leading the manufacturing of ash-based materials, as currently
3598 already performed in different EU Member States.

3599
3600 **Bio-waste** means biodegradable garden and park waste, food and kitchen waste from
3601 households, restaurants, caterers and retail premises and comparable waste from food
3602 processing plants. Across the European Union, somewhere between 118 and 138 million
3603 tonnes of bio-waste arise annually, of which currently only about 25% is effectively recycled
3604 into high-quality compost and digestate (European Commission, 2010a). The total P content
3605 of this fraction is unknown, but solid residues from the food processing industries (e.g.
3606 brewery, sugar industry) make up at least 36 kt P (see section 3.6).

3607
3608 **Co-digestion of animal manure with solid or slurried bio-waste of high methane**
3609 **potential such as oily residues and by-products, alcohol residues, digestible organic**
3610 **wastes from agri-processing and food industry or food waste, produces more gas from**
3611 **the digester than manure only** (Al Seadi and Lukehurst, 2012). Co-digestion can therefore
3612 improve the profitability of biogas plants, and is a common practice in many biogas facilities
3613 in Europe (Foget et al., 2011). In addition, co-digestion of animal manure and slurry with
3614 suitable organic wastes from food industries utilise the huge amounts of organic wastes that
3615 are produced annually and in many places otherwise dumped into landfills. The liquid
3616 fraction of co-digestates varies in phosphate content depending on the composition of the
3617 input materials; digestates that contain a dominant share of manure and food industry
3618 residues (e.g. sugar production, residues from the brewery industry) typically have phosphate
3619 contents above 500-2000 mg L⁻¹ PO₄³⁻P, whereas liquid digestate fraction produced from
3620 dominantly plant-based materials contain much lower phosphate contents (~0 - 500 mg L⁻¹
3621 PO₄³⁻P) (Akhlar et al., 2017).

3622

3623 8.2.4.2 Policy and legal framework

3624 The field extraction of crop residues and manure for STRUBIAS nutrient recycling processes
3625 manifestly result in the loss of nutrients and other valuable agronomic assets, such as soil
3626 organic matter. Therefore, it is clear that STRUBIAS nutrient recycling processes from these
3627 materials will only take place for reasons other than nutrient recycling close the site of
3628 extraction of manures and crop residues (hygienisation, transport logistics, synergies with
3629 energy recovery, etc.). Fundamentally, it is assumed that **significant materials from the**
3630 **agricultural sector might be used as input materials for STRUBIAS processes bearing**
3631 **in mind two different rationales:**

- 3632 i. **Pollution control:** in case of manure, in European regions characterised by nutrient
3633 excess and the need for the long-distance translocation of fertilising products to
3634 nutrient poor regions or the storage under appropriate conditions.
- 3635 ii. **Synergies with other bio-based materials:** secondary raw materials from the
3636 agricultural sector are used for STRUBIAS production processes as part of a

3637 cascading approach; in this case, the input materials for the STRUBIAS production
3638 processes are the residues of a process aimed at producing a different primary raw
3639 material from crop residues and manure, often renewable energy;

3640 Both rationales are not mutually exclusive and measures related to pollution control are
3641 mostly accompanied by additional benefits obtained through energy recovery.

3642

3643 As outlined in the Waste Framework Directive (Regulation (EC) No 2008/98), Member
3644 States shall take measures, as appropriate, and in accordance with Articles 4 and 13 of the to
3645 encourage (a) the **separate collection of bio-waste with a view to the composting and**
3646 **digestion** of bio-waste; (b) the treatment of bio-waste in a way that fulfils a high level of
3647 environmental protection; (c) **the use of environmentally safe materials produced from**
3648 **bio-waste**.

3649 **Pollution control**

3650 **International conventions** of relevance to P use in agriculture include inter alia UNEP/MAP
3651 (**United Nations Environment Programme/Mediterranean Action Plan**), CBD
3652 (**Convention on Biological Diversity**) and OSPAR (**Oslo & Paris Convention to prevent**
3653 **pollution**). Such international treaties often give an impetus to harmonise standards amongst
3654 all Member States of the European Union. Despite the significant off-site impact that diffuse
3655 contamination of P from agricultural land poses, there is no specific legislation that is directly
3656 concerned with the use of P in agriculture at European level. There is an insufficiency of
3657 appropriate institutional arrangements specific to the environmental pollution of P. Aspects of
3658 the P problem are, however, integrated in several policy areas and related legal instruments at
3659 European level. This section provides an overview of existing regulations and directives
3660 dealing with farm-level nutrients, including P, use and production at **European level**.

3661

3662 The **Water Framework Directive** (Directive 0060/2000) is a legal obligation to protect and
3663 restore the quality of waters across Europe. Measures applied under the Water Framework
3664 Directive affecting the use of P in agriculture relate to best environmental practices and
3665 include the reduction of nutrient application, the modification of cultivation techniques, the
3666 proper handling of pesticides and fertilisers, and the prevention of soil erosion through
3667 erosion minimising soil cultivation. The P balance surplus is a commonly used indicator for
3668 identifying areas vulnerable to nutrient pollution in the pressures and impacts analysis.

3669

3670 The **Nitrates Directive** (Directive 0676/1991) established in 1991 aims to reduce water
3671 pollution caused or induced by nitrates from agricultural sources and to prevent further nitrate
3672 pollution. The Water Framework Directive explicitly refers to the Nitrates Directive for
3673 information on diffuse pollution of nitrates from agricultural activities and extends this to
3674 phosphates. Under the Nitrate Directive, Member States had to establish action programmes
3675 for nitrate vulnerable zones with the purpose of meeting the objective of reducing and
3676 preventing nitrate pollution. It is the responsibility of each Member State to set limits
3677 appropriate to their vulnerable zones; there is no specific limits set in the Directive. However,
3678 the action programmes must include measures to ensure that, for each farm or livestock unit,
3679 the amount of livestock manure applied to land each year, including processed forms of

3680 manure and direct excretions by animals, shall not exceed 170 kg N per hectare. The
3681 measures established within the Action Programmes aim to control diffuse and direct water
3682 pollution and also to influence the use of P in farm practice. For instance, by limiting the
3683 annual application of N fertiliser and livestock manure, defining legally binding maximum
3684 concentrations of nitrates in drinking water and designating periods when the application is
3685 prohibited, the directive clearly aims at establishing and maintaining the natural balance of
3686 nutrients in soils. Through these measures a massive influx of nutrients to ground- and
3687 surface water and thus potential eutrophication is prevented, while excess nutrients,
3688 oversaturation and a possible ensuing soil quality degradation is avoided at the same time.
3689 The monitoring of waters for nitrate and the review of the eutrophic state of waters must be
3690 repeated every 4 years.

3691
3692 Pollution by P is also partially covered by the **Directive on Bathing Water** (Directive
3693 0007/2006), which together with the Nitrates Directive and the Industrial Emissions Directive
3694 has been linked since 2000 in the Water Framework Directive.

3695
3696 The **7th Environmental Action Programme** encourages the full implementation of the
3697 Water Framework Directive, in order to achieve levels of water quality that do not give rise
3698 to unacceptable impacts on, and risks to, human health and the environment.

3699
3700 **The Rural Development Programme** has established various agri-environment measures
3701 throughout the European Union directly or indirectly addressing diffuse contamination by P.
3702 Some of these measures are directed at mitigating soil erosion such as crop rotations, mulch
3703 seeding retaining stubble after harvest and ploughing restrictions. Other measures tackle the
3704 problem of excess nutrients through reduced fertiliser use. All measures that impact soil
3705 erosion and nutrient balances ultimately result in a reduction of diffuse contamination by
3706 phosphates from agricultural land.

3707
3708 The **Industrial Emissions Directive (IED, 2010/75/EU)** introduces an integrated cross-
3709 media approach, aiming to prevent or minimise emissions to air, water and land, as well as to
3710 avoid waste production with a view to achieving a high level of environmental protection as a
3711 whole. The IED Directive also concerns potentially polluting industries in the agricultural
3712 sector, among which are intensive pig and poultry farms. A single permit based on the
3713 concept of Best Available Techniques (BAT including limit values) must include all
3714 arrangements made, including emission limit values for pollutants, for water, air and land,
3715 and may, if necessary, contain requirements for the protection of the soil and the groundwater
3716 as well as measures or waste management (Art. 9(3)) in order to continuously prevent and
3717 reduce pollution. The purpose of the IED Directive was to achieve integrated prevention and
3718 control of pollution arising from several categories of industrial activities. The indicative list
3719 of main polluting substances to be taken into account if they are relevant for fixing emission
3720 limit values includes oxides of N and substances which contribute to eutrophication (P and
3721 N).

3722

3723 The main purpose of the **Habitats Directive** (Directive 0043/1992) and **Birds Directive**
3724 (Directive 0147/2009) is to ensure biological diversity through the conservation of natural
3725 habitats and wild flora and fauna within the European territory, while taking into account
3726 economic, social, cultural and regional requirements. Farmers who have agricultural land in
3727 Natura 2000 sites and face restrictions due to the requirements of the Habitat-Directive are
3728 eligible to receive payments for the management of these sites by the Rural Development
3729 Regulation, which helps promote environmental-friendly farming. Depending on the specific
3730 conditions of a certain area, these include measures to reduce the use of pesticides and
3731 fertilisers, measures to mitigate the effects of soil compaction, e.g. limitations on the use of
3732 machinery or the setting of stocking limits, or measures aiming to regulate the irrigation of
3733 agricultural land.

3734
3735 **Specific EU Member States** have set in place **national or regional regulations** to control
3736 for P use on farmland (Buckwell and Nadeu, 2016). Belgium-Flanders, Estonia, Finland,
3737 France-Brittany, Germany, Ireland, Luxembourg, Northern Ireland, Sweden and The
3738 Netherlands apply a regulation system that limits maximum P application rates. Limits are
3739 mostly dependent on crop type, soil P status and yield.

3740
3741 In spite of significant improvement in potential P surpluses within the EU, the **latest**
3742 **progress report on the implementation of the Water Framework Directive** (European
3743 Commission, 2015b) indicated that Member States need to strengthen their basic measures to
3744 tackle diffuse pollution caused by agriculture. Notwithstanding the fact that there is still a
3745 long way to go to achieving ‘good status’ (as defined in the Water Framework Directive)
3746 many Member States rely only on voluntary measures. Moreover, they need to ensure that
3747 their measures target the sources and chemicals that cause water bodies to fail to achieve
3748 ‘good status’. While these can effectively close a fraction of the remaining gap, significant
3749 improvement can only be achieved through compulsory basic measures. Member States
3750 should tackle the sources of pollution by fully implementing the Water Framework Directive
3751 measures and water-related legislation, especially the Nitrates Directive, Industrial Emissions
3752 Directive and Urban Waste Water Treatment Directive. This is much preferable to using end-
3753 of-pipe treatment, for instance to ensure the high quality of drinking water while avoiding
3754 high treatment costs and protecting the environment. Member States are encouraged to
3755 continue extending the establishment of safeguard zones to protect areas used for the
3756 abstraction of drinking water, in particular as regards surface waters.

3757
3758 **The last report on the Nitrates Directive** (European Commission, 2013b) points to a slight
3759 improvement in groundwater nitrate pollution while stressing the need for further action to
3760 reduce and prevent pollution. This is confirmed by the analysis of "Programmes of Measures"
3761 reported by the Member States. Despite the fact that 63% of river basin districts reported that
3762 implementation of the Nitrates Directive is not enough to tackle diffuse pollution to the level
3763 needed to meet Water Framework Directives objectives, necessary measures have not been
3764 added to address the remaining shortcomings. Diffuse pollution still affects 90% of river
3765 basin districts, 50% of surface water bodies and 33% of groundwater bodies across the EU.
3766 The agricultural sector is the primary source of diffuse pollution. **The report indicates that**

3767 **there are still many gaps in the basic measures put in place by Member States to**
3768 **address agricultural pressures, including a lack of measures to control phosphate and**
3769 **nitrate emissions outside nitrate vulnerable zones established under the Nitrates**
3770 **Directive.**

3771

3772 Supplementary measures reported in agriculture are largely voluntary, including advice
3773 schemes and agri-environment measures of the **Common Agriculture Policy (CAP)** such as
3774 **farm extensification and organic agriculture.**

3775 **Renewable energy**

3776 Renewable Energy Sources contribute to **climate change mitigation** through the reduction of
3777 greenhouse gas emissions, achieve sustainable development, protect the environment and
3778 improve citizens' health. Moreover, renewable energy is also emerging as a driver of
3779 inclusive economic growth, creating jobs and reinforcing energy security across Europe.

3780

3781 These aspects are enshrined in Article 194 of the Treaty on the Functioning of the EU, which
3782 has conferred Union competences to promote renewable energy. The EU has long been a
3783 world leader in the promotion and development of renewable energy, steering the effort to
3784 combat climate change, encouraging the shift to a low-carbon economy and stimulating high-
3785 potential economic growth.

3786

3787 The current 2020 framework sets an **EU 20% target for energy consumption** which relies
3788 on legally binding national targets until 2020. **National Renewable Energy Action Plans**
3789 **(NREAPs)** and the biennial monitoring provided for by Directive 2009/28/EC on the
3790 promotion of the use of energy from renewable sources have been effective in promoting
3791 transparency for investors and other economic operators. This has favoured the rapid increase
3792 in deployment in the share of renewables from 10.4% in 2007 to 17.0% in 2015.

3793

3794 In October 2014, the European Council agreed the 2030 framework for climate and energy
3795 reaffirming the Union's long-term commitment to the ambitious EU strategy in renewable
3796 energies. **The new framework sets out the European Union target of at least 27% for the**
3797 **share of renewable energy consumed in the EU in 2030.** This target is binding at EU level
3798 and will be fulfilled through individual Member States' contributions guided by the need to
3799 deliver collectively for the EU. In addition, the new framework also enables the collective
3800 delivery to be done without preventing Member States from setting their own, including more
3801 ambitious, national targets. Member States can support renewable energy, subject to State aid
3802 rules.

3803

3804 To qualify for the Renewable energy Directive targets, materials consumed in the EU must
3805 comply with strict **sustainability criteria** provided in Article 17 of the Directive, in order to
3806 be eligible for financial support and to count towards the EU renewable energy target.
3807 Rigorous requirements are set in the Renewable energy Directive on the minimum level of
3808 greenhouse gas savings, appropriate land use, as well as monitoring requirements for any
3809 potentially adverse effects. Agricultural raw materials produced within the EU must be

3810 produced in accordance with the minimum requirements for good agricultural and
3811 environmental practices that are established in the common rules for direct support schemes
3812 under the common agricultural policy. **Using manure and agricultural residues as**
3813 **feedstock is highly advantageous as it does not augment pressure on land and water**
3814 **resources and offers very high greenhouse gas mitigation gains** (European Environment
3815 Agency, 2013a).

3816

3817 **Materials from the agronomic sector can contribute to renewable energy production**
3818 **through the production of biogas and the thermochemical conversion of solid biomass.**

3819 The resulting materials (i.e. digestates and ashes) are suitable intermediate or end materials of
3820 STRUBIAS production processes, including recovered phosphate salts, ash-based materials
3821 and pyrolysis materials.

3822

3823 The application of anaerobic digestion for biogas production remains widespread as a useful
3824 **bioenergy production** route due to the robustness of its main design configurations and
3825 pathways. Anaerobic digestion serves multiple purposes. It provides a treatment platform for
3826 decreasing large amounts of complex organic materials, converting the majority of such
3827 molecules into monomers i.e. methane and carbon dioxide (biogas) utilisable in the energy
3828 sector in multiple pathways. The EU Common Agricultural Policy (CAP, Pillar II - Rural
3829 Development Policy) mechanisms provide support for capital investments on farm or as part
3830 of local renewable energy initiatives, including providing grant aid for the installation of
3831 anaerobic digesters.

3832

3833 The produced digestate can be used as fertiliser for crops without any further processing.
3834 However, the need for efficient nutrient management, required by restrictions on manure
3835 applications in areas with high livestock density, make recovery and recycling from plant
3836 nutrients from manure and bio-based waste streams increasingly important for farmers. **The**
3837 **anaerobic treatment serves to improve the efficiency for nutrient recycling as solid–**
3838 **liquid separation procedures can be applied to separate the solid from the liquid**
3839 **digestate** (Möller and Müller, 2012). The solid phase may be characterized as an organic
3840 fertiliser comparable with solid animal manure with highly available N and P contents, best
3841 suited to application on arable land in order to increase soil humus reproduction and to
3842 substitute P-losses via harvested P-rich biomass such as grains. Separated liquid digestates
3843 are characterised as liquid N–K fertilisers. A digestate solid– liquid separation, with a target-
3844 oriented separate application of the liquid and solid phase, is, therefore, a technique for
3845 further improvement of the nutrient use efficiency upon return to the field (Möller and
3846 Müller, 2012).

3847

3848 The traditional substrates for anaerobic digestion plants in Europe are **agricultural/livestock**
3849 **residues** (manure and slurries), **biogenic waste** (food waste, municipal organic waste, etc.),
3850 **energy crops** (maize whole crop silage, sugar beet, grass silage), as well as **residues from**
3851 **food and agro-industries** (animal by-products from abattoirs, brewers' spent grains and
3852 solubles, etc.) (Drogs et al., 2015). More recently, residues from the **bioethanol** and the
3853 **biodiesel** industries are used. Producing biogas from dedicated energy crops, such as maize,

3854 sugar beet or wheat, requires careful analysis due to their land use implications. The
3855 emissions of greenhouse gases and acidifying gases such as ammonia from these systems are
3856 substantial. The use of specifically grown energy crops for biogas has thus been questioned
3857 due to sustainability concerns. Such energy cropping patterns are not 'environmentally
3858 compatible' according to the criteria of a 2006 EEA study (European Environment Agency,
3859 2006). Where manure or organic residential wastes are used, the greenhouse gas performance
3860 of biogas pathways is far better (European Environment Agency, 2013a). **Wastes and crop**
3861 **residues are currently underused and can contribute significantly to reaching EU**
3862 **bioenergy targets** (European Environment Agency, 2013a). The latter report projects that
3863 agricultural residues and organic waste would contribute 44% of the total supply for meeting
3864 the NREAP bioenergy targets for agriculture. Therefore, introducing new, cost-competitive
3865 and sustainable feedstock such as manure, straw and even grass, will be increasingly
3866 important for the biogas sector to deliver its full potential in the future energy scenario.

3867
3868 Biogas is a diverse energy source, suitable as a flexible and storable energy form. Between
3869 2000 and 2013 the production of biogas in Europe increased six-fold, from 2.2 to 13.5 Mtoe,
3870 with the main producers being Germany, UK and Italy, followed by the Czech Republic,
3871 France and the Netherlands. Germany is the leader in biogas production from biomass with
3872 more than 65% of the EU production in 2013 (Flach et al., 2015). For Germany, it was
3873 estimated that in the year 2011, approximately 20% of the animal wastes and the biomass
3874 harvested from an area of approximately 1.1 million ha were used as feedstock in biogas
3875 plants (Möller and Müller, 2012). Italy, the Czech Republic and the Netherlands followed
3876 with a production share of 14%, 5%, and 2%, respectively (Flach et al., 2015). The incentive
3877 for farmers in Germany to invest in biogas digesters is a guaranteed feed-in price for the
3878 generated electricity, which is considerably higher than that of electricity generated from
3879 fossil fuels, natural gas, coal, or nuclear sources. This feed-in price is guaranteed for 20 years
3880 from the erection of the plants. However, changes to the German renewable energy law in
3881 2012 and 2014 and similar policy changes in Italy, **reduced the attractiveness of investing**
3882 **in new plants (Flach et al., 2015)**. As a result, the further increase in biogas plants will be
3883 minimal. Instead, investments will focus on rejuvenating existing plants. Biogas production is
3884 increasing in the Czech Republic (driven by feed-in tariffs for the derived electricity) and
3885 Denmark (driven by the goal to use 50% of livestock manure for biogas production in 2020)
3886 (Flach et al., 2015). In France, the government seeks to increase the number of biogas
3887 facilities by means of investment support. However, administrative burden and a lack of
3888 profitability for investors limit the expansion. The development is also stagnant in the Slovak
3889 Republic and Hungary. Slovak energy distribution companies announced a blanket stop on
3890 connecting new electricity producing facilities (over 10 kW) to the grid until further notice.
3891 Hungary reports problems with green energy feed-in systems and the complicated non-
3892 harmonised investment licensing. In addition, low electricity purchase prices make further
3893 investments into biogas facilities economically unattractive. In the Netherlands, the low
3894 electricity prices have even led to a decline in biogas production.

3895

3896 Landfilling of biodegradable waste

3897 The **Landfill Directive (1999/31/EC)** obliges Member States to reduce the amount of
3898 biodegradable municipal waste that they landfill to 35% of 1995 levels by 2016 (for some
3899 countries by 2020). On 2 July 2014, the European Commission adopted a legislative proposal
3900 to review waste-related targets in the Landfill Directive as well as recycling and other waste-
3901 related targets in Directive 2008/98/EC on waste and Directive 94/62/EC on Packaging and
3902 Packaging Waste. The proposal aims at phasing out landfilling by 2025 for recyclable waste
3903 (including plastics, paper, metals, glass and bio-waste) in non-hazardous waste landfills,
3904 corresponding to a maximum landfilling rate of 25%.

3905

3906 *8.2.4.3 Anaerobic digestion followed by P-precipitation*

3907 The European Environment Agency that forecast a reduced growth rate for biogas production
3908 in Europe, with a predicted **annual growth rate of 3% for the period 2013-2020 based on**
3909 **the NREAPs** (European Environment Agency, 2016).

3910

3911 The anaerobic digestion process does not affect the content of phosphate in digestate, which
3912 is completely dependent on the content in the substrate. Nonetheless, the technique is a door-
3913 opener for manure solid-liquid separation processes (Foget et al., 2011).

3914

3915 **Box 3: Recovered phosphate salts from the liquid fraction of anaerobically digested materials**

3916

3917 To derive the substitution potential of P-fertilisers containing STRUBIAS materials from the
3918 eligible input materials that have undergone an anaerobic digestion process, following
3919 assumptions and calculations were made:

3920

3921 1) **Digestates from manure and specific food industries** are more suitable for P-recovery
3922 than digestates from crop residues and other biowaste materials due to the higher P content in
3923 the liquid digestate fractions. Although co-digestion of other organic materials (food waste,
3924 crop residues) is common practice, the liquid fraction of such digestates is typically low in
3925 phosphates that can be precipitated (Akhiar et al., 2017). Therefore, this assessment only
3926 takes into account the P present of anaerobically digested manures and solid residues of food
3927 processing industries.

3928

3929 2) In 2010, about 88 million tonnes of **manure**, excluding other organic materials as co-
3930 substrates, were anaerobically digested in the EU (Flotats et al., 2013). Anaerobic digestion is
3931 also a door-opener for separation processes and treatment of the liquid manure fraction
3932 (Foget et al., 2011). Using the average P-contents of Foget et al. (2011), the total manure P
3933 that is subjected to anaerobic digestion was estimated at 114 kT of P for the year 2010. The
3934 European Environment Agency (2016) indicates that biogas production from anaerobic
3935 digestion would roughly double in the period 2010-2020. After 2020, an annual 3% growth,
3936 similar to the period 2013-2020, was assumed. Therefore, it is assumed that the total volume
3937 of materials from the agricultural sector would increase by a factor 2.69 relative to the
3938 amounts processed by anaerobic digestion in the year 2010. Hence, **a total amount of 237**

3939 **million tonnes of manure would be processed through anaerobic digestion, with an**
3940 **estimated P content of 306 kt P.** This number is considered realistic; it equals the excess P
3941 that accumulates in soils from six livestock-dense Member States: Belgium, Denmark,
3942 Germany, France, the Netherlands, and the UK (based on data for the year 2005 by van Dijk
3943 et al., 2016).

3944
3945 3) P-rich residues from the **food processing industry** are taken into account (36 kt P yr⁻¹,
3946 mainly from sugar residues and brewery industries; for the reference year 2005). These P-
3947 estimates are assumed to at steady state for the year 2030.

3948
3949 5) It is assumed that **recovered phosphate salts are recovered from all anaerobic digesters**
3950 **that process manure and solid processing residues.** The possible non-compliance with this
3951 assumption is presumed to be counteracted by the fact that liquid manure fractions can also
3952 be obtained by solid-liquid separation techniques on raw manures; thus not after anaerobic
3953 digestion.

3954
3955 4) At present, the P-recovery process of **Stichting Mestverwerking Gelderland (SMG)** is
3956 the only process at TRL level 7-9 processes in Europe that processes P-rich digestate liquids
3957 that complies with the draft proposals of the STRUBIAS nutrient recovery rules. In this
3958 process, K-struvite is precipitated from the liquid digestate fraction. The cost assessment of
3959 the process indicates a solid business case for the plant in the Netherlands where manure
3960 treatment is associated with a gate fee, even without considering the revenues from the sales
3961 of the K-struvite. Given the estimate pricing of recovered phosphates in the future (see
3962 section 7.1), the return on investment of similar P-recovery systems is high. Therefore, it can
3963 be assumed that more operators might emerge in other livestock-dense EU regions in the near
3964 future.

3965
3966 5) Following solid/liquid separation of the digestate, between 10-30% of the total P content
3967 will end up in the liquid digestate fraction, and about 80-95% of this P in the liquid fraction
3968 can be recovered as recovered phosphate salts. Therefore, the total P-recovery efficiency
3969 from anaerobically digested manure varies between 8% and 28.5%. The exact numbers are
3970 highly dependent on the separation technology applied (Drosg et al., 2015). In order to
3971 estimate the P-recovery potential, **a P-recovery efficiency of 13.3% as indicated by SMG** is
3972 used.

3973
3974 6) The **relative agronomic efficiency (RAE_{PUE})** of recovered phosphate salts relative to
3975 synthetic and mined P-fertilisers is assumed to be 1.05 (see section 5.2.2).

3976
3977 7) Considering 1) - 6), **the 2030 P-recovery from anaerobically digested eligible input**
3978 **materials is estimated at 48 kt P yr⁻¹** ((306 kt P yr⁻¹ (manure) + 36 kt P yr⁻¹ (food
3979 processing) * 0.133 (recovery efficiency) * 1.05 (RAE)). It is estimated that these materials
3980 will be brought on the market directly as P-fertilisers or as part of a physical blend, and that
3981 their further processing in recovered phosphate salt derivatives (e.g. MAP, DAP, TSP,
3982 nitrophosphate, etc.) is unlikely.

3983
3984

3985 8.2.4.4 Thermochemical conversion processes of solid fractions from the agricultural sector

3986 The **poultry manure** fractions and other manure fractions that have undergone a **solid-liquid**
3987 **separation process** might be suitable for thermochemical conversion processes due to their
3988 relatively low moisture content. Both **thermal oxidation and pyrolysis spectrum**
3989 **techniques** are considered in the STRUBIAS project.

3990 Thermal oxidation

3991 Thermal oxidation processes have been widely used for the production of energy (electricity
3992 and power). **Poultry litter incinerators** in the UK (Fibrophos), IE (BHSL), the Netherlands
3993 (BMC Moerdijk), and some Scandinavian Member States produce approximately **150.000 -**
3994 **200.000 tonnes of poultry litter ash** per year in the year 2015, equalling an estimated
3995 recovery of about **12-16 kt P yr⁻¹** (assuming a P content of 8%). A best estimate of 14 kt P yr⁻¹
3996 is assumed.

3997
3998 The aim of bioenergy technologies is to convert biomass into different forms of energy
3999 including power, heat, combined heat & power (CHP) and liquid biofuels. **The primary aim**
4000 **of poultry litter combustion is the production of renewable energy** (Billen et al., 2015).
4001 The calorific power of poultry litter when used as a fuel is about half that of coal (Moore,
4002 2013). In order to meet NREAP expectations, **a compound annual growth of 7% over the**
4003 **period remaining up to 2020 would be necessary** (European Environment Agency,
4004 **2016**).

4005
4006 The CE Delft research firm established the environmental effects of nine different ways that
4007 poultry litter – from the chicken to the field – can be used (De Graaff et al., 2017). The study
4008 concluded that the production of electricity through thermal oxidation is the most **attractive**
4009 **and sustainable manner to process poultry litter from an environmental perspective**.

4010
4011 In section 5.2.3, a relative agronomic efficiency for the response variable phosphorus use
4012 efficiency (RAE_{PUE}) of 1.49 was observed. The accuracy of this value is, however, uncertain,
4013 because this value was based on only 4 cases. Data from a research study performed by
4014 Alterra Wageningen UR, cited in De Graaff et al. (2017) indicated a relative fertiliser
4015 efficiency varying from 37% to 100%. These data were not included in the meta-analyses of
4016 section 5.2.3 due to lack of detailed results. Therefore, the lower end estimate of **0.90 for**
4017 **RAE_{PUE} for poultry litter ashes was retained for further calculations**; this value
4018 corresponds roughly to the weighted mean of the data from section 5.2.3 and the results given
4019 in De Graaff et al. (2017).

4020

4021 Box 4: Ash-based materials from solid manure fractions

4022

4023 To derive the substitution potential of P-fertilisers containing STRUBIAS materials from
4024 solid manure fractions from the agricultural sector, following assumptions and calculations
4025 were made:

4026

4027 1) Only poultry litter is considered as input material for ash-based STRUBIAS materials as
4028 no TRL 7-9 thermal oxidation processes from other solid manure fractions have been
4029 described that produce P-fertilisers.

4030

4031 2) In 2015, a total amount of 150.000 – 200.000 tonnes of poultry litter was produced, with
4032 an estimated P content of 14 kt P.

4033

4034 3) An annual growth rate in energy production from solid biomass of 7%, forecasted by the
4035 European Environment Agency (2016) for the period 2013-2020, has been assumed for
4036 poultry litter and extended until the year 2030. Accumulated over the time period 2015-2030,
4037 this would imply an increase of renewable energy production from poultry litter manure by a
4038 factor 2.76. Expressed on a P basis, the total P recovered as poultry litter ash would equal 39
4039 kt P yr⁻¹ for the year 2030.

4040

4041 4) The agronomic efficiency of poultry litter ash (RAE_{PUE}) relative to mined and synthetic
4042 fertilisers is assumed to be 0.90.

4043

4044 5) Considering 1) – 4), the estimated P-recovery from solid material from the agricultural
4045 sector is estimated at 35 kT of P.

4046

4047 Pyrolysis spectrum techniques

4048 Gasification and pyrolysis can potentially convert a range of biomass types with high input-
4049 output efficiency and these are **therefore interesting technology options to convert**
4050 **residues and wastes that do not occur in large and geographically concentrated volumes**
4051 (Kretschmer et al., 2013). One of the advantages of pyrolysis spectrum techniques is that
4052 processing facilities can operate at a relative small scale, enabling the establishment of many
4053 small-scale facilities to process high-volume, geographically dispersed materials, such as
4054 excess manure, without excessive transport costs. Moreover, the syngas generated during the
4055 pyrolysis process can be used as an energy source to dry the manure input material, although
4056 the drying takes place to the detriment of renewable energy production. Starting from input
4057 materials that have not undergone a solid-liquid separation, this process pathway would
4058 therefore only marginally contribute to the production of renewable energy, but would be
4059 principally performed as a measure for pollution control.

4060

4061 Although no commercial thermochemical technologies using biomass at the time of writing
4062 have been identified in Europe, several commercial plants are close to piloting and
4063 operationalisation, both in Europe and rest of the world. The emerging technologies
4064 especially focus on **the treatment of the solid pig manure fraction**, as obtained after solid-
4065 liquid separation treatment. This issue is particularly relevant given that the highly diluted pig

4066 manure is associated with high transport costs, and most farmers have only a small surface
4067 area to dispose the slurry produced (Foget et al., 2011).

4068

4069 The EU funded **BioEcoSim** project (<https://www.bioecosim.eu/>) projects to process
4070 2.000.000 m³ of pig manure per year, resulting in a production of 62 kt of pyrolysis materials
4071 derived from pig manure (3 kt P, assuming a 5% P content in the resulting output material).
4072 The Japanese company **Hitachi-Zosen Limited** also aims to turn pig manure from Dutch and
4073 Belgian pig farmers into P-rich pyrolysis materials. The latter company has gained
4074 experience with the process from their operations in Japan. Production costs for P-rich
4075 pyrolysis materials are estimated at about 4 Euros per tonne of pig manure slurry (Smit et al.,
4076 2012), or about 4000 Euro per tonne P. It should be noted, however, that the material also
4077 contains other elements of interest that can be returned to the agricultural field (see below).
4078 The pyrolysis process reduces the mass of the digestate by 70%, significantly reducing
4079 transport costs to agricultural land.

4080

4081 The **market outlook for this STRUBIAS pathway is associated to a large degree of**
4082 **uncertainty** as the resulting pyrolysis material is the only output material that will be brought
4083 on the market. The **economic valuation of pyrolysis materials is at present, however,**
4084 **largely unknown**, as well as the degree of consumer confidence associated to the end-
4085 material. Pyrolysis materials from solid manures have a P content of about 4-6%, organic C
4086 (~ 30-60%) and the presence of other nutrients in smaller quantities such as N, Mg and K.
4087 Expressed on a P-basis, the producers of pyrolysis materials claim a higher sales price for
4088 pyrolysis materials than for traditional P-fertilisers, based on allegations of high agronomic
4089 efficiencies (> 100%, expressed on a P-basis relative to synthetic and mined fertilisers) and
4090 additional benefits from increased soil fertility (see section 7.1.3). Nonetheless, at present,
4091 scientific and experimental evidence is lacking that demonstrates the superiority of pyrolysis
4092 material compared to traditional P-fertilisers in terms of fertiliser efficiency (see section
4093 5.2.4).

4094

4095 **The production cost for P-rich pyrolysis materials derived from manure is higher than**
4096 **for synthetic and mined P-fertilisers.** Moreover, the **nutrient density** of the resulting
4097 pyrolysis material is much **lower**, resulting in a higher land application cost for pyrolysis
4098 materials relative to synthetic and mined P-fertilisers. Unless the high sales prices of the
4099 pyrolysis materials could be realised, **it is assumed that the market potential of pyrolysis**
4100 **material in the conventional agricultural sector is low to negligible in the short-term (<**
4101 **year 2030).** Given the lack of availability of concentrated P-fertilisers for organic farming,
4102 pyrolysis materials could potentially make an entry into the organic farming sector. **Given**
4103 **the limited availability of P-dense fertilisers that meet the principles and requirements**
4104 **for organic farming, it is believed that this STRUBIAS material might be demanded**
4105 **and traded in this sector.** Here, the higher price setting of P-rich pyrolysis materials relative
4106 to synthetic and mined P-fertilisers could potentially be compensated by the higher sales
4107 prices of organically-grown food products. Manure-derived pyrolysis materials could thus
4108 replace current organic P-inputs such as manure, compost, meat & bone meal and meat &
4109 bone meal ashes in the organic farming sector. It is, however, concluded that STRUBIAS

4110 materials produced through the pyrolysis of manure fractions **will not significantly**
4111 **contribute to the substitution of synthetic and mined P-fertilisers as the latter are only**
4112 **marginally used in this agricultural sector.**
4113

4114 8.2.5 STRUBIAS materials derived from slaughter residues

4115 8.2.5.1 *Introduction*

4116 **Animal by-products activities covered under this section include the by-products**
4117 **obtained from the treatments of entire bodies or parts of animals at slaughterhouses.**
4118 Rendering activities include the treatments of animal by-products both intended for and not
4119 intended for human consumption. The animal by-products industry handles all of the raw
4120 materials that are not directly destined for human consumption. **The use and disposal routes**
4121 **permitted are governed by Regulation (EC) No 1069/2009 laying down health rules as**
4122 **regards animal by-products and derived products not intended for human**
4123 **consumption.** Animal by-products are classified in three different categories of which
4124 category 2 and 3 can be used for the production of fertilisers. **The transformation of**
4125 **category 1 material into fertilisers is effectively prohibited by Regulation (EC) No**
4126 **1069/2009, even after incineration, as any produced ashes should be disposed of as**
4127 **waste.** The ban on the use of processed animal proteins in feed for animals farmed for food
4128 and pet food has led to the diversification of the animal by-products industry.

4129
4130 The **rendering industry** processes most of the **animal by-products not intended for**
4131 **human consumption** as well as a significant fraction of the **catering waste**, also having a
4132 legal status as animal by-product (European Commission, 2005). There appears to be a trend
4133 towards fewer slaughterhouses with increasing average throughputs, favouring the **central**
4134 **collection of the slaughterhouse residues** for possible further processing to STRUBIAS
4135 materials (European Commission, 2005). In the year 2016, the rendering industry processed
4136 about 12.4 million tonnes of animal by-products of category 2 (0.8 million tonnes) and 3
4137 (11.7 million tonnes) (EFPRA, 2017).

4138
4139 8.2.5.2 *Sector outlook for the rendering industry and material use*

4140 **The total meat consumption in the EU is expected to remain stable within the EU for**
4141 **the period 2016-2026** (European Commission, 2016b). After the recent recovery, EU-28 per
4142 capita consumption of meat products is expected to rise only slightly over the projection
4143 period, mainly as a result of the increase in meat consumption in the EU-13. However,
4144 developments in total meat consumption depend both on evolutions in per capita
4145 consumption and in total population numbers. The population in the EU-13 is projected to
4146 decline in the next years at such a rate that the per capita increase in meat consumption is
4147 almost completely flattened out by the shrinking population, resulting in only 35 000 t
4148 additional meat consumed by 2026. In the EU-15, by contrast, the population is still
4149 increasing and therefore, with stable per capita consumption, total meat consumption is
4150 expected to grow by 600 000 t by 2026. Combined, total EU meat production is expected to
4151 expand only slightly in the next 10 years, reaching 47.6 million tonnes. This can be mainly

4152 attributed to an increase in poultry meat production and to a lesser extent to pig meat
4153 production, while beef and veal production will decrease substantially. Production of poultry
4154 is expanding (+ 4.5% for the period 2016-2026, to a total value of about 15 million tonnes of
4155 meat produced), driven by a favourable domestic market. Pig meat production is expected to
4156 increase slightly (+0.1%, to a total value of about 23 million tonnes of meat produced),
4157 despite the environmental concerns. After a few years of increase, beef production is
4158 expected to return to its downward trend in the coming years (-8.6% for the period 2016-
4159 2026, to a total value of about 7.5 million tonnes of meat produced). By contrast, production
4160 of sheep and goat meat is likely to remain relatively stable after years of decline. **As EU**
4161 **consumption will not entirely absorb the moderate increase in production, the EU**
4162 **balance is stable due to somewhat increased export prospects** (European Commission,
4163 2016b).

4164
4165 Based on these meat production numbers, **a 2030 outlook of 11.5 million tonnes and 0.8**
4166 **million tonnes of animal by-product processing is predicted for category 3 and 2,**
4167 **respectively** (i.e. 98.5% of the volumes processed in the year 2016). The degreasing process
4168 then results in the production of ~2.9 million tonnes of protein-rich materials of category 2
4169 and 3 that contain the overall share of the P derived from animal bones, feathers, hairs, blood,
4170 etc. (Dobbelare, 2017). This material is known as meat and bone meal (category 2 materials)
4171 or processed animal proteins (PAP, category 3 materials). The P-concentrated bones (~10.5%
4172 P on a dry matter basis) contain the overall share of the P in the meat and bone meal, because
4173 the other animal fractions are characterised by a low P content (0.1% - 1.7%). Assuming an
4174 average P-content of 5.3% (Moller, 2015), **it is projected that the protein fraction of**
4175 **category 2 and 3 materials contains about 154 kt of P yr⁻¹.**

4176
4177 At present, the meat and bone meal of **category 2 material is already largely used for the**
4178 **production of fertilisers, mostly as meat and bone meal without any significant further**
4179 **processing** (Dobbelare, 2017). Also some category 2 materials are sent to incineration (for
4180 energy recovery), landfill or composting. Its use in pet food, feed or food materials is not
4181 permitted according to the provisions of Regulation (EC) No 1069/2009. **Category 3**
4182 **materials are used to a smaller extent for the production of fertilisers (~17%). Most of**
4183 **the materials are used in pet food (~65-70%), fish feed (~10%) and fur animal feed (5-**
4184 **10%).** Less than 5% of the category 3 materials are used for the production of terrestrial
4185 animal food, human food (gelatin) or incinerated (Dobbelare, 2017).

4186
4187 The proteins derived from processed animal by-products are thus intensively used for the
4188 production of different materials. As a consequence of the many different competing uses,
4189 **meat and bone meal and processed animal proteins are traded at a price of about 50-70**
4190 **Euro per tonne, or about 943 – 1320 Euro per tonne P.** The bone fraction is even traded at
4191 a higher price, expressed on P-basis.

4192

4193 8.2.5.3 *Thermochemical conversion processes*

4194 Meat and bone meal has a heating value ranging between 13000 and 30000 MJ per tonne
4195 (Conesa et al., 2003). Therefore, a thermal treatment by combustion, gasification or pyrolysis
4196 could potentially be used to generate energy.

4197 **Incineration**

4198 When incinerated, the ashes derive mostly from the bone component and contain high
4199 amounts of Ca and P, mainly hydroxyapatites and tricalcium phosphates. The combustion
4200 induces a wide range of structural modifications, reducing the P-solubility relative to the
4201 unburnt meat and bone meal (Moller, 2015).

4202

4203 **Co-incineration of meat and bone meal is at present the foremost treatment for category**
4204 **1 materials that should be disposed of.** However, according to Article 32 of the Animal By-
4205 Products Regulation (EC No 1069/2009), Category 1 derived materials cannot be placed on
4206 the market as organic fertilisers or soil improvers.

4207

4208 **The fertiliser industry has already successfully tested the use of Category 2 and 3 meat**
4209 **and bone meal ashes in the acidulation process** for the production of mineral P-fertilisers
4210 (Langeveld and Ten Wolde, 2013). Meat and bone meal ashes can effectively substitute
4211 phosphate rock in the process due to their high P content similar to phosphate rock, their
4212 consistency, their low Al and Fe content and their low levels of metals/metalloids (especially
4213 the Cd content is much lower than in phosphate rock). The chemical composition of the
4214 fertilisers (partly) produced from incinerated protein-based animal by-products is equal to
4215 that of fertilisers that are currently on the market (DAP, MAP, TSP, SSP, nitrophosphate, etc;
4216 depending on the choice of the production process). In any case, the contaminant profile of
4217 the fertiliser end-material will be different, with metals/metalloids – especially Cd - being
4218 present in lower contents in P-fertilisers derived from meat and bone meal ashes. Also, the
4219 environmental impact of producing fertiliser using these secondary phosphate sources
4220 suggests the emissions of phosphate and fluorine is lower than when using regular phosphate
4221 rock (Langeveld and Ten Wolde, 2013).

4222

4223 From an economic point of view, meat and bone meal and processed animal proteins of
4224 Category 2 and 3 material (943 – 1320 Euro per tonne P, see section 8.2.5.2) are more
4225 expensive than phosphate rock (on average 649 Euro per tonne P; see section 7.1.3).
4226 However, in contrast to phosphate rock, the combustion of meat and bone meal and processed
4227 animal proteins will enable energy recovery. **Thermochemical P-fertiliser production**
4228 processes such as the Mephrec process, the FEhS/Salzgitter process, and the thermo-
4229 reductive Recophos process (see paragraph 4.2.2) use meat and bone meal as an input
4230 material, **effectively reducing the energy demand of such processes.** Meat and bone meal
4231 is used as a fuel and as a P-source in the above-mentioned STRUBIAS production processes
4232 that produce phosphoric acid and ashes/slugs that can directly be used as a P-fertiliser. The P-
4233 recovery rates of these processes are high, with values ranging from 80% to 89% (see
4234 paragraph 4.2.2). Moreover, meat and bone meal ashes are a P-rich material (~14%, Moller,
4235 2015) low in Al/Fe oxides, for which reason they could also be used to **increase the**

4236 **suitability of combustion ashes**, either directly as a fertiliser or as an intermediate in P-
4237 fertiliser production processes (Vamvuka et al., 2017).

4238

4239 **Box 5: Ash-based materials from slaughter residues**

4240

4241 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
4242 this route, following assumptions and calculations were made:

4243

4244 1) For the year 2030, the total incoming P in the protein fraction of category 2 and 3 materials
4245 contains is assumed **154 kt of P yr⁻¹**. In line with Regulation EC 1069/2009, category 1
4246 animal by-products are not considered in this assessment.

4247

4248 2) It is assumed that the increased demand of meat and bone meal and processes animal
4249 proteins in P-fertilisers will lead to a new equilibrium for the use and fate of category 2 and 3
4250 animal by-products. The rate of adjustment to bring markets to the long run equilibrium
4251 depends on various factors, such as the degree of technological change or market conditions,
4252 and cannot be clearly determined at the moment. In this preliminary assessment, it is
4253 **assumed that material use for the production of STRUBIAS P-fertilisers will increase to**
4254 **half of the total fraction, or 77 kt of P yr⁻¹**. The STRUBIAS sub-group is invited to provide
4255 techno-scientific data that can further refine this estimate.

4256

4257 3) The assumed **P-recovery rate is on average 85% of the P present in the protein**
4258 **fraction.**

4259

4260 4) It is assumed that the materials will be used in thermal and wet-chemical manufacturing
4261 processes that aim at improving the agronomic efficiency of the materials relative to raw
4262 ashes. The relative agronomic efficiency (RAE_{PUE}) of thermal and wet-chemical processes is
4263 estimated at 0.85 and 1.00, respectively (see section 5.2.2). **A mean RAE value of 0.92 is**
4264 **assumed.**

4265

4266 5) Considering 1) - 4), **the P-recovery from slaughter residues is estimated at 61 kt of P**. It
4267 is estimated that these materials will be brought on the market as P-fertilisers that are already
4268 available on the market (e.g. MAP, DAP, TSP, etc.) or as P-fertilisers that have chemical
4269 composition similar to Thomasphosphates and Rhenaniaphosphates.

4270

4271

4272 Pyrolysis of animal bone materials

4273 Animal by-products of Category 2 and 3 could also be processed via pyrolysis spectrum
4274 techniques, **resulting in a P-rich material that is embedded in a matrix of stabilised C**. At
4275 present, the only TRL 7-9 production pathway is the so-called 3R pyrolysis process, where
4276 animal bone materials are heated further up to 850°C. During the pyrolysis process all
4277 volatile and protein based substances are removed from the mineral matrix, and a highly
4278 macro-porous apatite type mineral material is produced, composed of hydroxyapatite (70-
4279 76%), CaCO₃ (7-13%) and carbon (9-11%), with a P content of 13% (30 P₂O₅) (3R
4280 AgroCarbon, 2016).

4281

4282 Similar to the market for pyrolysis materials derived from manure, the **market outlook for**
4283 **this STRUBIAS pathway is associated to a large degree of uncertainty** as the resulting
4284 pyrolysis material is the only output material that will be brought on the market. The
4285 **economic valuation of pyrolysis materials is at present, however, largely unknown**, as
4286 well as the degree of consumer confidence associated to the end-material. Expressed on a P-
4287 basis, the producers of pyrolysis materials claim a higher sales price for pyrolysis materials
4288 than for traditional P-fertilisers based on allegations of high agronomic efficiencies (> 100%,
4289 expressed on a P-basis relative to synthetic and mined fertilisers) and additional benefits from
4290 increased soil fertility. Nonetheless, at present, scientific and experimental evidence is
4291 lacking that demonstrates the superiority of pyrolysis material from slaughter residues
4292 compared to traditional P-fertilisers in terms of fertiliser efficiency. Preliminary test results
4293 seem to point to a relative agronomic efficiency (RAE_{PUE}) that is, at a maximum, close to a
4294 value of 1 (thus equivalence to mined and synthetic P-fertilisers; see section 5.2.4).

4295

4296 **The production cost for P-rich pyrolysis materials derived from animal bone material is**
4297 **higher than for synthetic and mined P-fertilisers**. Unless the high sales prices of the
4298 pyrolysis materials could be realised, **it is assumed that the market potential of animal**
4299 **bone-derived pyrolysis material in the conventional agricultural sector is low to**
4300 **negligible in the short-term, i.e. before the year 2030**. Given the lack of availability of
4301 concentrated P-fertilisers for organic farming, pyrolysis materials could potentially make an
4302 entry into the organic farming sector. It is re-iterated that the use of mined and synthetic
4303 fertilisers is heavily restricted under the existing legislation (Council Regulation (EC) No
4304 834/2007 on organic production and labelling of organic products). Synthetic resources and
4305 inputs may only be permissible if there are no suitable alternatives. Such products, which
4306 must be scrutinised by the Commission and EU countries before authorisation, are listed in
4307 the annexes to the implementing regulation (Commission Regulation (EC) No. 889/2008).

4308

4309 Animal bone biochar would be the most P-dense fertiliser having a P content similar to
4310 phosphate rock, but with an improved plant P-availability. Therefore, the higher price setting
4311 of animal bone biochar relative to synthetic and mined P-fertilisers could potentially be
4312 compensated by the higher sales prices of organically-grown food products. Here, animal-
4313 bone derived pyrolysis materials could potentially replace current organic P-inputs such as

4314 manure, compost, meat and bone meal and meat and bone meal ashes in the organic farming
4315 sector. **Given the limited availability of P-dense fertilisers that meet the principles and**
4316 **requirements for organic farming, it is believed that there might be a potential demand**
4317 **for animal bone-derived pyrolysis materials in the organic farming sector.** A market
4318 entry in this sector may also enable further long-term product testing under realistic
4319 circumstances. It is, however, assumed that STRUBIAS materials produced through the
4320 pyrolysis of animal bone materials will **not significantly contribute to the substitution of**
4321 **synthetic and mined P-fertilisers** as the latter are only marginally used in this agricultural
4322 sector.

4323

4324 8.2.6 STRUBIAS materials from municipal wastewaters

4325 8.2.6.1 Introduction

4326 Historically, the P present in materials resulting from municipal wastewater treatment plants
4327 was largely returned to the agricultural field as sludge. Due to the physical-chemical
4328 processes involved in the wastewater treatment, the sludge tends to concentrate heavy metals
4329 and poorly biodegradable trace organic compounds as well as potentially pathogenic
4330 organisms (viruses, bacteria, etc.) present in wastewaters. Sludge is, however, rich in
4331 nutrients such as N and P and contains valuable organic matter that may prove useful when
4332 soils are depleted or subject to erosion. Sludge is usually treated before disposal or recycling
4333 in order to reduce its water content, its fermentation propensity or the presence of pathogens.
4334 Several treatment processes exist, such as anaerobic digestion, thickening, dewatering,
4335 stabilisation and disinfection, and thermal drying. The sludge may undergo one or several
4336 treatments. Once treated, **sludge can be recycled or disposed of using three to four main**
4337 **routes: recycling to agriculture (landspreading), composting, incineration or landfilling.**

4338

4339 The direct or indirect return of sewage sludge to agricultural land through these routes might
4340 be associated to emissions of pollutants into the soil, and indirect emissions into air and
4341 water. Other emissions into the air include exhaust gases from transportation and application
4342 vehicles. Although the EU Sludge Directive 86/278/EEC enables the return of treated sludge,
4343 some **Member States have adopted national regulations with provisions that go beyond**
4344 **the requirements of the Directive 86/278/EEC** (see section 8.2.6.2). **Therefore, the**
4345 **fraction of sewage sludge that is disposed of is increasing in Europe.** The disposal of
4346 sludge is considered by most stakeholders to have the disadvantage of wasting the fertilising
4347 value of the sludge.

4348

4349 **STRUBIAS materials can be produced from nutrient-rich materials originating from**
4350 **wastewater treatment plants, and thus provide a possibility for the safe return of P**
4351 **present in sewage to agricultural land.** Specifically, municipal wastewaters and sewage
4352 sludges are listed as eligible input materials for recovered phosphate salts and ash-based
4353 materials.

4354

4355 8.2.6.2 *Policy and legal framework*

4356 **European legislation**

4357 The legal framework established by the European Commission and regulating the various
4358 sludge routes is mainly composed of Directives which have to be transposed into national
4359 legislation by Member States. These Directives are listed in Appendix 1. The ones most
4360 relevant to sludge management are the following:

- 4361 • Council Directive of 21 May 1991 concerning urban wastewater treatment
4362 **(91/271/EEC), known as the Urban Waste Water Treatment Directive**, is aimed at
4363 protecting the environment from the adverse effects of wastewater discharges. This
4364 Directive sets minimum sewage treatment standards to be achieved in stages by the
4365 end of 2005, and provides for advanced wastewater treatment for the removal of
4366 nitrogen and phosphorus from sensitive areas. Sensitive areas are defined as: areas
4367 particularly susceptible to eutrophication, surface waters intended for the abstraction
4368 of drinking water with high nitrate levels, and other waters that require a higher
4369 standard of treatment to satisfy the requirements of other Directives. Directive
4370 91/271/EEC supports the use of sewage sludge in article 14: "sludge arising from
4371 waste water treatment shall be re-used whenever appropriate";
- 4372 • Council **Directive 86/278/EEC on the protection of the environment when sewage**
4373 **sludge is used in agriculture**. This Directive sets minimum quality standards for the
4374 soil and sludge used in agriculture, and defines monitoring requirements when sludge
4375 is spread on agricultural land. The limit values defined in this Directive concern heavy
4376 metals concentration for sewage sludge as well as for soil when sewage sludge is used
4377 on land and maximum annual heavy metals loads through the application of sewage
4378 sludge
- 4379 • Sludge applications in agriculture must also comply with limits set by other EU
4380 legislation on nutrients in the environment, such as the **Nitrates Directive**
4381 **(91/676/EEC)** that limits the amounts of nitrates in water;
- 4382 • The **Waste Framework Directive (Directive 2008/98/EC)** confirms the waste
4383 management hierarchy; preference has to be given to waste prevention followed by
4384 waste reduction, re-use, (nutrient) recycling, and energy recovery. This Directive
4385 establishes principles for the use and disposal of waste, waste management plans,
4386 approval procedures and monitoring;
- 4387 • The Directive on the **landfill of waste 1999/31/EC** restricts disposal of sludge to
4388 landfill, by gradually reducing the allowed quantities of biodegradable waste going to
4389 landfill and prohibiting the landfilling of both liquid and untreated wastes;
- 4390 • **Directive 2010/75/EU on industrial emissions** sets limit values for emissions of
4391 pollutants to air from waste incineration.

4392

4393 **Outlook for sewage sludge treatment and management options in Europe**

4394 The current trend in sewage sludge treatment is to reduce the amount of sewage sludge that is
4395 landfilled due to the increasing costs and increasing legislative restrictions on the landfilling

4396 of biodegradable waste (Milieu Ltd - WRc - RPA, 2010c). **This leaves two mid to long-term**
4397 **options for the fate of sewage sludge: (1) landspreading – possibly after treatments such**
4398 **as anaerobic digestion and composting, and (2) incineration.**

4399

4400 The provisions of the Waste Framework Directive (Directive 2008/98/EC) oblige the
4401 Member States to expressly apply the **waste hierarchy** as a priority order in legislation and
4402 policy. In accordance with Article 4(2) of Directive 2008/98/EC, when applying the waste
4403 hierarchy, **Member States must take measures to encourage the options that deliver the**
4404 **best overall environmental outcome.**

4405

4406 There is scientific evidence that the **landspreading of sewage sludge to agriculture can**
4407 **provide agronomic benefits**, in particular the recycling of plant nutrients such as N and P.
4408 Indeed, one of the most commonly recognised environmental benefits is the recycling of P in
4409 the food chain. This contributes to the conservation of P reserves and also reduces external
4410 inputs of Cd originating from phosphate rock. Sludge also provides other plant
4411 macronutrients, such as K and S, and micronutrients such as Cu and Zn. The beneficial
4412 effects of sludge application on soil organic matter status, structural properties and soil
4413 moisture retention are also well documented. **The accumulation and recycling of**
4414 **contaminants present in the sewage sludge is, however, a major concern when**
4415 **determining environmental impacts**, especially in population-dense regions where limited
4416 land is available for the spreading of sewage sludge close to wastewater treatment plants.
4417 Environmental impacts of transport of the high-volume sludge should also be considered.
4418 **Benefits in terms of climate change and greenhouse gases emissions** from recycled
4419 sewage sludge to agriculture are claimed, in particular that a portion of the C in sludge used
4420 in agriculture will be sequestered in the soil. However, it remains unknown to what extent the
4421 long-term effect is **scientifically substantiated and, at present, national inventories of**
4422 **greenhouse gas emissions do not consider sequestered carbon from sludge used in**
4423 **agriculture (Milieu Ltd - WRc - RPA, 2010b).**

4424

4425 The environmental impacts associated to incineration are dependent on whether the sludge is
4426 combusted in mono- or co-incinerators. In simple terms, **co-incineration will score better on**
4427 **impacts related to global warming potential and energy recovery, whereas mono-**
4428 **incineration enables the potential recovery of P at the expense of a lower energy**
4429 **recovery potential.** The energy content of sludge is better used when it is co-incinerated at a
4430 coal-fired power plant compared to mono-incineration (de Ruijter et al., 2015). This is caused
4431 by a different design of the plants, where the advantage of a coal-fired plant comes from a
4432 larger scale and use of inputs with a lower corrosive effect. Ashes from a coal-fired plant,
4433 however, are not suitable for P recovery because of their low P content. Requirements for
4434 flue gas cleaning are stricter for mono-incinerators compared to coal-fired power plants. The
4435 oven of a mono-incinerator is designed for a specific type of input and including another type
4436 of input would require another oven. This means that current co-incinerated inputs cannot
4437 simply be diverted to existing mono-incinerators.

4438

4439 The fact that recycling of nutrients has a higher priority than energy recovery in the waste
4440 hierarchy suggests **that mono-incineration followed by P-recovery from the ashes may be**
4441 **the preferred incineration option.** This observation is even more important given that P is a
4442 finite element, and phosphate rock is itemised on the EU list of critical raw materials.
4443 Moreover, **benefits for environmental protection and human health safety are assured** as
4444 ash-based STRUBIAS materials will have to comply with contaminant limits in the proposed
4445 revision of the Fertiliser Regulation that are more strict than the provisions of the sludge
4446 Directive 86/278/EEC. The complex technologies and operational costs required to extract
4447 and produce materials from sewage sludge make this route, however, **less cost efficient in**
4448 **comparison to landspreading.** The cost for landspreading of semi-solid or digested sludge is
4449 about 126-185 Euro per tonne sludge (dry matter basis), whereas the cost for the mono-
4450 incineration of sewage sludge is estimated at 411 Euro per tonne sludge (dry matter basis)
4451 (Milieu Ltd - WRc - RPA, 2010c). Mono-incineration of sewage sludge thus increases
4452 treatment costs with a factor 2.2 - 3.2. The supplementary cost is, however, only 3% of the
4453 total costs for wastewater treatment and disposal (Nätörp et al., 2017). Significant
4454 investments in mono-incinerators would be required in specific Member States. At present,
4455 only Austria, Belgium, Denmark, Germany, the Netherlands and the UK - all of them EU-13
4456 countries - have operational dedicated sewage sludge mono-incinerators (European
4457 Commission, 2017a). A total of 43 mono-incinerators are present in Europe, of which the
4458 overall share (23) is located in Germany (European Commission, 2017a). For cities and
4459 regions where infrastructure with mono-incinerators is available and P-rich ashes are already
4460 generated, **recovering P from ashes with best available ash-process techniques is**
4461 **associated to little or no additional costs (compared to ash disposal) if revenues from P-**
4462 **fertilisers sales are taken into consideration** (Egle et al., 2016). This is exemplified by the
4463 agreement between EcoPhos and Dutch mono-incinerating facilities (60.000 tonne of sewage
4464 ashes per year), indicating the commercial viability to transform P-rich mono-incineration
4465 ashes into high-value P-sources such as pure DCP.

4466
4467 There is an ongoing debate on the best practices for the recycling of sewage sludge to the
4468 field, and **Member States continue to differ widely in the weighing of environmental,**
4469 **social and economic impacts associated to sewage sludge management** (Milieu Ltd - WRc
4470 - RPA, 2010b). The uncertainty related to future sewage sludge handling routes makes it
4471 highly challenging to provide an accurate estimate on the market for STRUBIAS materials
4472 derived from sewage sludge.

4473
4474 **Germany and Austria have already taken up a clear position** and are currently
4475 transposing the provisions of the Waste Framework Directive into national legislation that
4476 **makes the recovery of P from mono-incinerated sewage sludge ashes mandatory.** In
4477 **Austria,** The draft Federal Waste Plan 2017 (Bundes-Abfallwirtschaftsplan) includes a ban
4478 of direct land application or composting for sewage sludge generated at Wastewater
4479 Treatment Plants with capacities of 20 000 people equivalents or above within a transition
4480 phase of 10 years. These wastewater treatment plans will have to recover the P from sludge
4481 targeting P contents below 20 g P / kg dry solids in the rest fraction, or have to deliver their
4482 sludge to sludge mono-incinerators. The P is then to be recovered from the sewage sludge

4483 ashes obtained. This regulation will cover 90% of the P contained in the Austrian municipal
4484 wastewater. In **Germany**, the new sewage sludge ordinance will make phosphorus P
4485 recovery from sewage sludge obligatory for all German wastewater treatment plants with a
4486 capacity larger than 50,000 person equivalents (p.e.). They will have to recover the P if the
4487 sludge contains more than 2% phosphorus /DS (dry solids) or have to incinerate the sludge in
4488 mono-incinerators. Land application of sludge will only be allowed under strict conditions for
4489 wastewater treatments plants < 50,000 p.e. The ~500 plants that are projected as subject to
4490 the requirement of P-recovery represent roughly 66% of the total P removed from German
4491 wastewater and transferred into the sludge. The **Swiss Ordinance on the Avoidance and**
4492 **Disposal of Waste** (VVEA) came into force in 2016. The recovery of P from phosphorus-
4493 rich waste, i.e. effluent sludge and animal and bone meal not recovered as feed has become
4494 legally binding at ordinance level, with a 10-year transitional period. Given a 10-year grace
4495 period, P-recovery will have to be implemented until 2026. Current studies are on-going to
4496 determine the on-the-ground implementation (e.g. minimal recovery rates).

4497
4498 The implementation of the **EU directive on waste water treatment and sludge handling** in
4499 the other Member States varies considerably. Certain Member States have implemented
4500 stricter provisions for the landspreading of sludge than those of Council Directive
4501 86/278/EEC, especially in terms of maximum allowed levels of heavy metals and organic
4502 compounds. **In particular, in countries such as Austria, Belgium, Denmark, Finland,**
4503 **France, Germany, Luxembourg, the Netherlands and Sweden, the limit values in**
4504 **national regulations are extremely stringent**, although use in agriculture at present still
4505 remains an important outlet for sludge in these countries. The landspreading of sewage sludge
4506 is already banned or highly restricted in the Netherlands and Belgium-Flanders, and – after a
4507 transition period – in Austria and Germany. The reasons for restricting landspreading relate to
4508 concerns on pollutants and the objective to reduce competition for the return of organic
4509 materials to the available land in the form of manure. **In the United Kingdom, Portugal,**
4510 **Spain, and the EU-13 countries, farmers' associations and authorities support the**
4511 **agricultural use of sludge, both for economic and for agronomic reasons** (mainly in terms
4512 of providing an economically feasible option for the return of organic matter and P to the
4513 agricultural field). Spain, for instance, has issues related to soil erosion and desertification,
4514 and so the recycling of sewage sludge to agricultural land is the preferred option, as indicated
4515 in the National Sewage Sludge Plan of wastewater treatment plants 2001-2006: "As long as
4516 sewage sludge complies with legal requirements, including those which might be established
4517 in the future (...) it is considered that the most sustainable option is the recycling of nutrients
4518 and organic matter by agricultural land application" (art. 1.3.). Italy, Greece and Ireland have
4519 not taken up a strong position on sludge recycling in agriculture, as far as can be judged from
4520 the available information.

4521
4522 STRUBIAS materials could be recovered in the form of recovered phosphate salts and ash-
4523 based material from municipal wastewaters and the resulting sludges. The 2030 outlook for
4524 the latter could be estimated as follows:

- 4525 • The total amounts of wastewaters that will be treated in the EU and sludges that will
4526 be generated are expected to increase in the future due to the increased

4527 implementation of the Urban Waste Water Treatment Directive (91/271/EEC). An
4528 annual increase of 13% in sewage sludge volumes has been estimated for the period
4529 2010-2020 within the EU-28 (Milieu Ltd - WRc - RPA, 2010b). If this growth rate is
4530 extrapolated to the **year 2030, the total incoming P in municipal waste water**
4531 **treatment plants would be estimated at 360 kt of P** (based on the sum of P in
4532 communal sewage sludge and urban waste water treatment effluent for the year 2005;
4533 van Dijk et al., 2016).

4534 • Milieu Ltd – WRc - RPA (2010b) indicated a decadal 18% increase in incinerated
4535 sludge for the period 2010-2020. When this growth rate is extrapolated to the year
4536 2030, **the share of sludge disposal through incineration would equal 37%**. This
4537 value corresponds reasonably to the sum of the sewage sludge amounts that are
4538 currently already incinerated (27.3%) and landfilled (9.2%) (based on available data
4539 from Eurostat averaged for the period 2010 - 2012; this period corresponds to the
4540 latest EU-28 representative reporting period). In line with the Waste Framework
4541 Directive provisions that prioritise nutrient recycling over energy recovery and the
4542 impossibility to recover P from co-incinerated sludge, **it is assumed that mono-**
4543 **incineration is the single route for incineration**. Potentially, the high costs of
4544 investment and operation required for a mono-incinerator can be partly off-set by the
4545 increased revenues from the valorisation of mono-incinerated ashes and higher gate
4546 fees for sewage sludge ashes. The possible non-compliance with the highly ambitious
4547 100% mono-incineration assumption is presumed to be counteracted by sludge shifts
4548 from landspreading towards the incineration routes. The reduced acceptance for
4549 landspreading and possible stricter (national or EU) legislation on contaminant levels
4550 in landspreaded sewage sludge, and the possible synergies of incineration with energy
4551 recovery could drive shifts in sewage sludge management.

4552

4553 8.2.6.3 Trade-offs between process pathways

4554 Phosphorus can be recovered upstream in the wastewater treatment facility as recovered
4555 phosphate salts or downstream from the resulting sludges and mono-incinerated sludge ashes
4556 (section 4). Basically, it is relevant to distinguish two relevant configurations:

- 4557 i. The sludge is recovered downstream from the resulting sewage sludge treatment, after
4558 the mono-incineration of the produced sludge. In this case, **most (~95%) of the**
4559 **incoming P in the wastewater can be recovered**. Note that P-recovery technologies
4560 exist for sewage sludge ashes that have been produced using chemical precipitation
4561 and EBPR techniques (see section 4.2). P-recovery from the sludge can also occur
4562 after upstream P-recovery from the sludge liquor or digested sludge in EBPR
4563 treatment facilities **with a recovery of 10-15%** (first generation struvite production
4564 processes; see section 4). In this case, the resulting sludges will still contain sufficient
4565 P (>85%) to enable P-recovery in a present-day techno-economic perspective;
- 4566 ii. Specific processes that **recover P from pre-treated (e.g. after thermal hydrolysis)**
4567 **sludges** either upstream in the waste water treatment process (e.g. Cambi process; that
4568 releases roughly 50% from the sludge matrix into the liquid sludge liquor) or

4569 downstream on the generated sludge (e.g. Budenheim process) **show P-recovery**
4570 **rates of about 40-50%**. Such processes, however, produce sludges that contain only
4571 the remaining 50-60% of the P, making them less suitable for landspreading (low
4572 P/contaminant ratios) and economically viable P-recovery in the form of ashes.

4573

4574 With a view on the obligation to recover the dominant P fraction from municipal wastewaters
4575 in the Waste Framework Directive, option ii) is associated to a major disadvantage. The
4576 legislative proposals in Germany and Austria effectively require P-recovery rates of >50%,
4577 and thus restrict the viability of configurations described in point ii). **For the estimation of**
4578 **the potential of STRUBIAS materials to substitute synthetic and mined P-fertilisers,**
4579 **only route i) is considered.**

4580

4581 *8.2.6.4 P-precipitation from sludge liquor and digested sludge at biological wastewater* 4582 *treatment plants*

4583 The Urban Waste Water Treatment Directive (91/271/EEC) requires that more advanced
4584 treatment (tertiary treatment) is required for discharges into sensitive areas (cf. Article 5 of
4585 the Directive). According to the latest summary report on urban wastewater treatment
4586 (European Commission, 2011), a total of 72.8% of EU-27 territory was identified as sensitive
4587 area/catchment of sensitive area and therefore requires more stringent treatment. The territory
4588 of sensitive areas in EU-28 increased by 4.8% compared to the last Implementation Summary
4589 of the year 2001 (i.e. 4.8 % increase/decade). In 2011, tertiary treatment was in place for 89%
4590 of the load for EU-15 and for 27% of the generated load for EU-12 (European Commission,
4591 2011). As the infrastructure in place cannot always achieve quality standards in line with the
4592 Directive's requirements, 79% of the total generated load for EU-15 and 24% of the total
4593 generated load for EU-12 were reported to work adequately (European Commission, 2011).
4594 For the 2030 market estimate, it is assumed that the growth in sensitive areas will lead to an
4595 equivalent growth rate for wastewater treatments that rely on tertiary treatment (i.e. 4.8% per
4596 decade for the period 2010 – 2030). Therefore, **the total generated load for adequately**
4597 **operating wastewater treatment plants with tertiary treatment in the year 2030 is**
4598 **estimated at 83% and 26% for EU-15 and EU-13, respectively.** Given that ~75% of the
4599 disposed sludge is generated in the EU-15 (Eurostat, 2017), **a weighted average for the EU-**
4600 **28 of the relative wastewater load connected to tertiary treatment is estimated at 69%.**

4601

4602 The most popular P removal techniques to remove P from wastewater treatment effluents are
4603 enhanced biological phosphorus removal (EBPR) and the more widely used chemical
4604 phosphorus removal (Chem-P) using iron or aluminium salts. Although no exact data are
4605 available for the EU as a whole, Wilfert et al. indicated **that in Western Europe, exclusive**
4606 **use of Chem-P is the dominant configuration for P removal in wastewater treatment**
4607 **(around 60%; expressed on sludge produced or people equivalents).** The remaining 40% of
4608 the plants rely on EBPR or EBPR with Chem-P support, configurations that would enable the
4609 P-recovery as recovered P-salts from the digested sludge or the sludge liquor (see section 4).
4610 Excluding pre-treatments such as thermal hydrolysis, these processes have a recovery rate of

4611 about maximal 15% and can provide substantial benefits for the functioning, maintenance
4612 and sludge handling for EBPR waste water treatment plant (improved sludge dewatering,
4613 reduced pipe clogging, etc.). Therefore, these processes are considered economically viable,
4614 especially if also the revenues from the sales of the recovered phosphate salt are taken into
4615 consideration. This route of P-recovery is technically impossible for wastewater treatment
4616 plants that rely exclusively on Chem-P techniques.

4617
4618

Box 6: Recovered phosphate salts from the sludge liquor and digested sludge at EBPR
wastewater treatment plants.

To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
this route, following assumptions and calculations were made:

1) For the year 2030, the total incoming P in municipal waste water treatment plants would is
estimated at **360 kt of P**.

2) 69% of the EU-28 urban wastewaters will be processed with **tertiary treatment**. Struvites
are produced at 100% of the EBPR wastewater treatment plants and EBPR plants with Chem-
P support in Europe.

3) For the year 2030, the current **share of the plants with tertiary treatment that partly
rely on EBPR configurations is maintained** (40%). At present, there is no clear techno-
scientific or economic evidence that justifies a radical change in wastewater treatment plant
configurations, for which reason only minor shifts can be expected in sludge that is treated in
the year 2030. Given 1) and 2), EBPR wastewater treatment plants will treat about 99 kt P
yr⁻¹.

4) The **assumed P-recovery rate is 15%** of the P present in the incoming P content of the
wastewater.

5) The **relative agronomic efficiency** (RAE_{PUE}) of recovered phosphate salts relative to
synthetic and mined P-fertilisers is assumed to be 1.05 (see section 5.2.2).

6) Considering 1) - 5), **the P-recovery from** the sludge liquor and digested sludge at EBPR
wastewater treatment plants **is estimated at 16 kt of P**. It is estimated that these materials
will be brought on the market directly as P-fertilisers or as part of a physical blend, and that
their further processing in recovered phosphate salt derivatives (e.g. MAP, DAP, TSP,
nitrophosphate, etc.) is unlikely.

4650
4651
4652

4653 8.2.6.5 Sewage sludge mono-incineration

4654 Egle et al. (2016) indicated the techno-economic **viability of P recycling from mono-**
4655 **incinerated sewage sludge ashes**. The P-recovery from Chem-P wastewater treatment
4656 configurations is somewhat more challenging than from EBPR sludges. Nonetheless, specific
4657 chemical and thermochemical processes can handle such materials, possibly thanks to the
4658 simultaneous incorporation of such Fe/Al-rich ashes with more suitable input materials such
4659 as phosphate rock in the production process. **Processes of high TRL level such as the**
4660 **acidulation process, the Ecophos process and thermo-reductive RecoPhos process (ICL)**
4661 **all produce inorganic intermediates (H_3PO_4 , P_4) that can be used to produce**
4662 **conventional, mineral P-fertilisers (MAP, DAP, DCP, SSP, TSP, nitrophosphate, etc.).**
4663 Given that these end-materials are associated to a high degree of market and consumer
4664 readiness in the conventional sector, the manufacturing of such end-materials is a highly
4665 probable route. Other routes that produce P-fertilisers of a different chemical composition are
4666 associated to a higher production cost and lower market readiness (lack of comprehensive
4667 testing on agronomic value, P present in less concentrated form resulting in higher transport
4668 and application costs, etc.). Therefore, it is unlikely that such materials will conquer a
4669 significant share of the conventional agricultural market, but minor volumes of such slow P-
4670 release fertilisers could be possible traded in niche markets and/or organic farming sectors.

4671
4672 **The bottleneck that will limit the volumes of recovered P-fertilisers derived from sewage**
4673 **sludge is the relative share of sludge that will be subject to the (cost-intensive) mono-**
4674 **incineration.**

4675
4676 As indicated in section 8.2.6.2, **it is estimated that 37% of all generated sludge will be**
4677 **treated via mono-incineration followed by P-recovery in the year 2030.**

4678
4679

4680 Box 7: Ash-based materials from mono-incinerated sewage sludge ashes

4681

4682 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
4683 this route, following assumptions and calculations were made:

4684

4685 1) The calculations are based on the **full implementation of the provisions of the Waste**
4686 **Framework Directive** (Directive 2008/98/EC) that requires that P is effectively recovered
4687 from waste water treatments, either through landspreading of the sludge or through the return
4688 of STRUBIAS materials to the agricultural field.

4689

4690 2) For the year 2030, **the predicted P-content in sewage sludges corresponds to 95% of**
4691 **the P present in the incoming waste water minus the P contents that are already**
4692 **recovered upstream** in the form of recovered P-salts (see section 8.2.6.4). Hence, the
4693 maximal total P in municipal sewage sludges is estimated as $(360 \text{ kt P yr}^{-1} * 0.95) - 15 \text{ kt P}$
4694 $\text{yr}^{-1} = 327 \text{ kt P yr}^{-1}$.

4695

4696 3) A total of **37% of the total P present in municipal sewage sludges will be mono-**
4697 **incinerated**, after which on average 95% of the P will be recovered from the ashes.

4698
4699 4) The recovered P will be used to produce water-soluble mineral P-fertilisers that have, per
4700 definition, a **100% relative agronomic efficiency relative** to their mined counterparts.

4701
4702 5) Given 1) to 5), a **P-substitution potential of 115 kt of P yr⁻¹ through this route is**
4703 **estimated with ash-derivates as end-material of the production process.**
4704

4705 4706 4707 4708 8.2.7 STRUBIAS materials derived from food processing industry wastewaters

4709 According to the assessment of van Dijk et al. (2016), the P-losses from this sector were
4710 estimated at a moderate 44 kt P for the year 2005, of which about 8 kt P occurs as wastewater
4711 effluents.

4712
4713 **Wastewaters from certain food processing industries are rich in P, either because of the**
4714 **properties of the source material (e.g. dairy industry, sugar beet industry) or due to the**
4715 **P-rich additives applied to the production processes (e.g. potato industry).** At present,
4716 STRUBIAS materials are recovered as P-fertilisers from the potato industry and dairy
4717 industry as struvite, included in the STRUBIAS category "recovered phosphate salts". To the
4718 best of the authors' knowledge, these are currently the only TRL 7-9 processes that
4719 manufacture P-fertilisers meeting the conditions as outlined for PFC 1. Nutrient recovery
4720 processes from other residual waste water streams from food processing industries have not
4721 been documented. The underlying reasons for this observation remain unknown, but may be
4722 associated to the **spatial scattering of the food processing facilities** (i.e. lack of central
4723 collection possibilities of the wastewaters and sludges), **the chemical composition of the**
4724 **waste water** (a phosphate content < 50 mg P L⁻¹ making them unsuitable for precipitation as
4725 Ca- or Mg-phosphates), **the transfer to urban waste water treatment plants**, or the **direct**
4726 **return to agricultural land of the uncontaminated sludges and waste waters.** With the
4727 exceptions indicated for specific food industries, waste waters from other food processing
4728 industries are mostly characterised by rather low phosphate contents, for which reason they
4729 are unsuitable for P-recovery in the form of recovered phosphate salts. **Therefore,**
4730 **production processes from food processing industries, other than those from the dairy**
4731 **and potato industry, are not considered in this 2030 market assessment.**
4732

4733 The P-losses from the dairy industry are more difficult to estimate. The phosphate contents in
4734 the wastewaters vary largely between facilities, but most plants rely on the use of Fe
4735 coagulants in order to meet effluent quality requirements in line with the Water Framework
4736 Directive (Crittenden et al., 2008). **The suitability of the wastewater for P-recovery in a**
4737 **more plant-available form (e.g. struvites) will vary with wastewater characteristics**
4738 **across dairy plants.**

4739
4740

4741 **Box 8: Recovered phosphate salts from the food processing industry**

4742

4743 To derive the substitution potential of P-fertilisers containing STRUBIAS materials through
4744 this route, following assumptions and calculations were made:

4745

4746 For the year 2030, there is a potential for P-recovery in the form of recovered phosphate salts
4747 from **wastewaters from the potato industry and the dairy industry**. P-precipitation from
4748 other food processing industries is not considered due to a lack of current TRL 7-9 processes.
4749 Other STRUBIAS pathways are not considered as the thermochemical conversion of
4750 wastewaters from the food processing industry will not produce sludges that can be converted
4751 to P-fertilisers via incineration or pyrolysis.

4752

4753 A. Potato industry

4754 At present, more than 8.3 million tonnes of potatoes are processed in Belgium and the
4755 Netherlands. In theory, 1 tonne of recovered phosphate salt can be precipitated as struvite
4756 from 500 tonnes of potatoes (Schuurmans Stekhoven, 2015), resulting **in a total maximal**
4757 **recovery potential of about 16.6 kt of struvite per year (~ 2 kt P yr⁻¹)**.

4758

4759 B. Dairy industry

4760 About 2-3% of the incoming milk is lost during cleaning operations, via washing steps and
4761 through occasional milk spills (Hach company, 2017). Typically, milk contains 1 kg of P per
4762 tonne. In 2015, about 150 million tonnes of milk was collected by dairies in Europe (Eurostat,
4763 2017). By multiplying these numbers, the total P recovery potential from the dairy sector
4764 would equal 3 - 4.5 kt of P. Under the assumption that the precipitation of recovered
4765 phosphate takes place with a recovery efficiency of 75%, **the maximal potential P-recovery**
4766 **from the dairy industry is about 2-3 kt of P**.

4767

4768 The increased monetary valorisation of recovered phosphate salts will provide a competitive
4769 advantage over chemical P-removal, at least for the largest facilities that process large
4770 amounts of waste waters of high P-content. Assuming that 25-75% of all wastewater
4771 treatment plants from the potato and dairy industry would rely on Ca and/or Mg salts for
4772 precipitation, **results in a total P-recovery potential of 1-3 kt of P yr⁻¹, with a best**
4773 **estimate of 2 kt of P yr⁻¹**. Note that, at present, about one third (640 t P yr⁻¹) of this value is
4774 realised.

4775

4776

4777

4778 **8.2.8 STRUBIAS materials derived from the metallurgic industry**

4779 Slags are produced as residues from the metallurgic industry through a variety of techniques
4780 (see section 3.8). Due to their high Ca and P contents, slags from the iron and steel industry
4781 are currently applied on land as P-fertilisers or liming materials. The ratios of slag to steel

4782 output indicate that large volumes of slags are produced. Manufacturing a tonne of pig iron
4783 produces, for instance, 0.25–0.30 tonnes of blast furnace slag that can be further granulated to
4784 granulated blast furnace slag (Jewell and Kimball, 2014). The output mass of blast oxygen
4785 furnace slag per tonne of crude steel is 0.10–0.15 tonnes (Jewell and Kimball, 2014).
4786 Altogether, slags from the steel industry are produced in Europe in an amount of
4787 approximately **25 - 40 million tonnes** (Branca et al., 2014; European Commission, 2016a).
4788

4789 Iron slag and steel slag are used primarily as aggregates in concrete, asphaltic paving, fill, and
4790 road bases. Slags can also be used as a feed for cement kilns. About 2-3 percent of the slags,
4791 representing > 800 000 tonnes, are used as for the production of **fertilising products**
4792 (European Commission, 2016a). In Germany, slag use as fertilisers and liming materials has a
4793 long tradition; about half a million tonnes of steel industry lime are used in agriculture. Slag
4794 can be used as a liming material or P-fertiliser production and micro-nutrients supply. The
4795 marketing of these products is today a reality in Germany, Austria, Finland, Sweden, France
4796 and probably other Member States. Basic slags are an effective liming material, having a high
4797 content of Ca (25 – 30%) and some Mg. The relative agronomic efficiency of such materials
4798 remains unknown; the RAE_{DMY} for electric arc furnace steel slags was estimated at 0.46 (see
4799 section 5.2.3; based on data from Bird and Drizo (2009)). However, the steel industry is
4800 currently testing processes that aim to increase the quality of the output materials (e.g.
4801 FEhS/Salzgitter process; see section 4.2.2). With P contents varying between 4.4% and 9.6%
4802 (Gendebien et al., 2001), steel industry slags are thus nowadays an important P source for the
4803 European agriculture. Altogether, the use of steel industry slags in European agriculture is
4804 **estimated at about 26 kt P yr⁻¹** (i.e. 812 500 tonnes material x 7% P x 46% relative
4805 agronomic efficiency). This estimate is kept for the year 2030, but more information is
4806 requested from the STRUBIAS sub-group to make a more informed estimate in upcoming
4807 reports (see below).
4808

4809 The European steel association estimates that the potential use of slags in agriculture could
4810 reach 1 500 000 tonnes across the EU. This has to be considered as a low estimation as the
4811 UK and Poland, which have still a strong steel industry, have not replied to the survey
4812 (European Commission, 2016a). It remains, however, to be evaluated to what extent the P-
4813 fertilisers derived from the steel industry will meet the proposed levels of metals/metalloids
4814 that will be set at CMC or PFC level.
4815

4816 Question 4 to the STRUBIAS sub-group:

4817
4818 Please provide an outlook for slags from the steel industry that are intended for use in
4819 agriculture. More specifically, information is requested on following aspects:

- 4820 • Evolution in supply and demand for steel industry slags that are used as P-fertilisers in
4821 agriculture, as well a realistic outlook for the market outlook for the year 2030. Please
4822 express numbers in absolute tonnes of material per year, indicating the P concentration, or
4823 in kt P per year. Please provide separate datasets for different types of slags (blast furnace
4824 slag, basic oxygen slag, etc.).

- 4825
- 4826
- 4827
- 4828
- 4829
- 4830
- 4831
- 4832
- 4833
- 4834
- 4835
- 4836
- Data on the content of metals/metalloids (specifically B, Ba, total Cr, Cr (VI), Co, Cu, Hg, Mn, Mo, Ni, Pb, Sb, and V) in the different types of slag. Please provide full datasets or descriptive statistics indicating the 10th, 25th, 50th, 75th and 90th percentile of the distributions.
 - At present, it remains unclear if the production process is adapted in order to improve the quality of the resulting slag, or if any supplementary processing is performed on the raw slags obtained to increase their value as a fertilising material. Please provide any relevant information.
 - Information on the relative agronomic efficiency of different output STRUBIAS materials.
 - Evolution of the average sales prices of steel industry slags in the last decade and future outlook (Euro per tonne material and P concentration, or Euro per tonne P).

4837

4838

4839 8.2.9 Other process pathways and eligible materials not considered

4840 To the best of the authors' knowledge, all P-fertilisers as defined by the minimum P₂O₅

4841 contents for PFC 1 produced through STRUBIAS production processes from eligible input

4842 materials are covered in the sections 8.2.4 - 8.2.8. Other STRUBIAS production processes

4843 (e.g. thermochemical conversion materials from biowaste, pulp and paper industry sludge,

4844 woody biomass, etc.) may lead to marketable fertilising products, but likely under different

4845 PFC categories (e.g. liming materials, soil improver, biostimulants, etc.). Therefore, these

4846 production processes will be covered in the separate section 8.3.

4847

4848 Question 5 to STRUBIAS sub-group:

4849

4850 Please indicate any additional process pathways that result in the formation of P-fertilisers

4851 (pursuant definition and criteria of P-fertilisers as given for PFC 1 in the proposal for the

4852 Revised Fertiliser Regulation) and describe their market outlook in terms of volumes of P that

4853 could be produced by the year 2030. The proposed pathways should meet following

4854 conditions:

- 4855
- 4856
- 4857
- 4858
- 4859
- 4860
- 4861
- 4862
- 4863
- Derived from eligible input materials for each of the three STRUBIAS material groups as outlined in JRC Interim Report on nutrient recovery rules as distributed in May 2017 or derived from eligible input materials that were not listed, but are nonetheless in line with environmental and human health safety aspects and agronomic efficiency as indicated by techno-scientific evidence.
 - Associated to a technological readiness level of stage 6-9.
 - Realistic from an economic point of view based on the current and expected costs/gate fees for input materials, production processes, and revenues of generated output materials

4864

4865

4866 8.2.10 Conclusion

4867 8.2.10.1 Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative
4868 framework

4869 **The estimates given in sections 8.2.4 - 8.2.8 are subject to many uncertainties and as a**
4870 **result should only be interpreted with the necessary precaution.** This is due to
4871 uncertainties regarding existing data sources, the future development in technology, the
4872 legislation in place for the year 2030, consumer confidence in STRUBIAS materials, the
4873 development of alternatives for dealing with eligible input materials, and the preliminary cost
4874 assessments. The results are based on the information gathered, including the responses from
4875 consultations, **and therefore represent the best estimate currently possible with the**
4876 **information available.** For selected STRUBIAS production processes, the JRC will evaluate
4877 costs and impacts on the environment and human health. These techno-economic analyses
4878 may serve as a basis to validate the information provided, and make the necessary corrections
4879 on market potential, where relevant.

4880
4881 Summing up the best estimates for the production of STRUBIAS materials from manure,
4882 municipal waste waters, slaughter residues, the food processing **industry, and the**
4883 **metallurgic industry a total of 302 kt of plant-available P could be recovered as**
4884 **recovered phosphate salts and ash-based materials** (Table 12). Although there could be a
4885 market for **pyrolysis materials**, the 2030 market potential **remains indeterminate** due to the
4886 lack of comprehensive test results on agronomic efficiency for this STRUBIAS group.
4887 Therefore, it remains unclear if farmers are willing to pay for a material that is traded at
4888 prices that exceed those of mineral P-fertilisers, expressed on a monetary basis per unit of P
4889 present in the material.

4890
4891 STRUBIAS materials expected to be on the market in 2030 are **almost exclusively derived**
4892 **from municipal waste waters (43%), manure (27%) and slaughter residues (20%)**
4893 (Table 12). Although significant progress has been made, the current handling of P in the
4894 sewage sludge and manure is not fully in line with the principles of sustainable use and
4895 recycling, because large P amounts from these sources are accumulating in soils, landfilled or
4896 removed from the biogeochemical P cycle in the form of construction materials (Schoumans
4897 et al., 2015). The applicable legislative framework and policy impacting upon water and soil
4898 quality are therefore heavily determining the STRUBIAS market and trade potential.

4899
4900 It is estimated that **ash-based materials will be the dominant STRUBIAS output material**
4901 **group with a total estimated production volume of 236 kt P yr⁻¹** or 78% of all STRUBIAS
4902 materials (Table 13). It is estimated that a major share of ash-based materials will be brought
4903 on the market in a **chemical form that is already available on the market** (DAP, Map,
4904 SSP, TSP, nitrophosphate). Such materials may have a competitive advantage because of the
4905 high consumer confidence associated to these products in the conventional agricultural
4906 market. It is estimated that also the market for **recovered phosphate salts (66 kt P yr⁻¹**; 22%
4907 of the total plant-available P recovered as STRUBIAS) will grow exponentially in the coming
4908 years (Table 13), mainly due to **process benefits at wastewater treatment plants that rely**

4909 **on enhanced biological P-removal techniques and synergies between P-recovery and**
4910 **renewable energy production in anaerobic digesters.**

4911

4912 **For specific fertiliser materials, and especially those derived through pyrolysis**
4913 **processes, the organic farming sector is a potential trade market.** The use of high-quality
4914 struvite and calcinated ashes for the organic farming sector has already been positively been
4915 evaluated by the sector, and possibly more STRUBIAS materials can be authorised under the
4916 existing legislation on organic farming in the EU (Council Regulation (EC) No 834/2007 on
4917 organic production and labelling of organic products). In this market, materials are often
4918 traded at a higher price and few P-dense fertiliser alternatives are authorised in this sector. At
4919 present, about 6% of the utilisable agronomic area is destined for organic farming in the EU.
4920 A market entry into the organic farming could enable comprehensive testing of the material
4921 quality, especially for agronomic efficiency. These results could potentially open an avenue
4922 towards expansion within the conventional agricultural sector, where STRUBIAS materials
4923 could replace and complement other P-sources of organic nature.

4924

4925 **Most P-recovery in the form of STRUBIAS materials will take place in Western**
4926 **Europe.** The regional distribution of STRUBIAS production pathways is mainly a result of
4927 issues related to renewable energy production through digestates, high livestock densities that
4928 lead to P-excess in soils and possible issues related to water eutrophication, and reduced
4929 acceptance for the landspreading of sewage sludge (Table 12). With ash-based materials as
4930 the dominant STRUBIAS pathways, EU Member States that have mono-incineration
4931 facilities also have a competitive advantage for STRUBIAS production (reduced
4932 infrastructure investments). Nonetheless, it should be noted that incineration ashes will also
4933 be shipped to facilities in other European regions (e.g. EcoPhos manufacturing site in
4934 Bulgaria).

4935 **Table 12: Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative framework, the importance of the different processes**
 4936 **across EU regions, and the major market drivers that will positively stimulate the market (values given are best possible estimates based on the**
 4937 **information available and are subject to a high degree of uncertainty and as a result should only be interpreted as a rough approximation of the total**
 4938 **estimates).**

process pathway	section	recovered STRUBIAS material	recovered total P (kt P yr ⁻¹)	relative agronomic efficiency (%)	recovered bio-available P (kt P yr ⁻¹)	share of total bio-available P recovered (%)	regional distribution in Europe	major market drivers that will stimulate the market
P-precipitation after anaerobic digestion, dominantly from manure	8.2.4.3.	recovered phosphate salts	45	105	48	16	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), renewable energy targets.
thermal oxidation of solid manure fractions	8.2.4.4.	ash-based materials	39	90	35	12	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), renewable energy targets.
thermal oxidation of slaughter residues	8.2.5.3.	ash-based materials	65	92	61	20	livestock dense regions	synergies with energy recovery from animal by-products
P-precipitation from biological municipal wastewater treatment plants	8.2.6.4.	recovered phosphate salts	15	105	16	5	regions and cities that apply tertiary treatment at water treatment plants	increased share of biological waste water treatment plants.
thermal oxidation of sewage sludge	8.2.6.5.	ash-based materials (derivates of well-known chemical composition (e.g. DAP, MAP))	115	100	115	38	regions with low acceptance for sewage sludge landspreading and mono-incineration capacity	focus on increased soil protection from metal accumulation and nutrient excess, ban on landfilling of biodegradable waste.
P-precipitation from the food processing industry	8.2.7	recovered phosphate salts	2	105	2	1	regions with dairy and potato processing industries	focus on externalities and costs associated to industry waste water discharges.
thermal oxidation of iron ores	8.2.8.	ash-based materials (slags)	56	46	26	9	regions with high densities of steel making companies	increased costs associated to landfilling.
pyrolysis materials of solid manure fractions	8.2.4.4.	pyrolysis materials	indeterminate	indeterminate	indeterminate	indeterminate	livestock dense regions having soils showing P-excess and water bodies subject to P-eutrophication	reducing externalities due to manure excess (water quality), soil quality improvement, increased consumer and market acceptance.
pyrolysis of slaughter by-products	8.2.5.3.	pyrolysis materials	indeterminate	indeterminate	indeterminate	indeterminate	potentially somewhat more important in livestock dense regions	increased consumer and market acceptance.
OVERALL TOTAL			337		302	100		

4939

4940 **Table 13: Market estimate for TRL 7-9 processes under the anticipatable 2030 legislative framework as aggregated per STRUBIAS material group**
 4941 **and per input material (values given are best possible estimates based on the information available and are subject to a high degree of uncertainty**
 4942 **and as a result should only be interpreted as a rough approximation of the total estimates).**

	P content (kt P yr-1)	relative contribution (% of total)
<i>Aggregated per STRUBIAS material group</i>		
Recovered phosphate salts	66	22
Ash-based materials	236	78
Pyrolysis materials	indeterminate	not considered
<i>Aggregated per input material</i>		
manure	78	27
municipal wastewater	131	43
slaughter residues	61	20
food processing industry	7	1
metallurgic industry	26	9

4943

4944 8.2.10.2 *Further market stimulations*

4945 The inclusion of STRUBIAS CMCs in a revised EU Fertiliser Regulation could significantly
4946 contribute to increasing the sustainability in the EU agricultural sector and reducing negative
4947 externalities of production and consumption patterns. These topics are high on the political
4948 EU agenda that includes ambitious targets for waste recycling, water quality improvements,
4949 and reducing human exposure to contaminants. Although highly challenging to quantify, it is
4950 believed that shifting policy agenda targets towards 2030 plus further developments of
4951 specific TRL 6 processes could further stimulate the potential 2030 market for P-fertilisers
4952 derived from STRUBIAS materials. **Positive feedback loops induced by legislation could**
4953 **possibly further increase the production volumes of STRUBIAS materials, especially in**
4954 **case of acceptable implementation costs.**

4955
4956 There is a continued political and public focus on externalities caused by the agricultural
4957 sector as well as on concerns on newly emerging pollutants (e.g. personal care products and
4958 pharmaceuticals). The recycling of P from manure and sewage sludge in the form of high-
4959 quality STRUBIAS materials can contribute to reducing nutrient leaching to water bodies and
4960 decreasing the accumulation of contaminants in soils **compared to reference scenarios of**
4961 **landspreading**. The **P use efficiency** of STRUBIAS materials is typically larger than for
4962 these organic P sources because the release of P can be better synchronized with plant needs,
4963 thus reducing the scope for its loss to deeper soil layers and surrounding water bodies.
4964 Moreover, benefits are associated to the improved logistics for P-material storage, transport
4965 and handling, **improving the efficient return of nutrients to P-depleted soils and regions**.
4966 Finally, STRUBIAS production pathways for recovered phosphate salts and ash-based
4967 materials could effectively reduce organic and inorganic contaminants from the input
4968 materials, and thus **reduce the abundance of contaminants in the environment** relative to
4969 some of the currently applied business-as-usual scenarios (e.g. land spreading).

4970
4971 [Note that preliminary information on this topic provided in the Background Document of the
4972 Kick-off Meetings on such impacts is currently under validation by JRC. These aspects will
4973 be further elaborated in a separate section as a part of the Final Report of the impact
4974 assessment study.]

4975
4976 The below-mentioned scenarios include examples of such further progress on legislative and
4977 policy measures that could stimulate the production volumes of STRUBIAS materials. Note
4978 that the second scenario is based on the breakthrough of promising technological
4979 developments for manure fractions; this assumption is reasonable as there are various TRL 6
4980 processes that show a significant 2030 market potential.

4981
4982 1. As part of an ex-ante impact assessment, the European Commission has already
4983 investigated the impact of restricting the application of sewage sludge on soil (Milieu Ltd -
4984 WRc - RPA, 2010a). Any changes in Council Directive 86/278/EEC of 12 June 1986 on the
4985 protection of the environment, and in particular of the soil, when sewage sludge is used in
4986 agriculture will largely impact the STRUBIAS market potential. An option that has been

4987 investigated is to introduce, for instance, **more stringent standards on heavy metals in**
4988 **landspreaded sewage sludge** (option 3 – stricter limits on heavy metals as described in
4989 Milieu Ltd - WRc - RPA, 2010c). Under such possible new provisions, 53% of all sewage
4990 sludge would have to be incinerated. Under such a scenario the total P recovered from
4991 municipal waste waters would increase from 112 kt P yr⁻¹ to 170 kt yr⁻¹ (+ **58 kt yr⁻¹**).

4992

4993 2. As indicated in section 8.2.4, EU Member States should tackle the sources of pollution by
4994 fully implementing the Water Framework Directive measures and water-related legislation,
4995 especially the Nitrates Directive, Industrial Emissions Directive and Urban Waste Water
4996 Treatment Directive. In the present assessment, a total amount of 83 kt of recovered P is
4997 recovered from the agricultural sector, a number that is in line with the P that is lost to
4998 surrounding water bodies (81 kt of P yr⁻¹; van Dijk et al., 2016). However, also about 924 kt
4999 P yr⁻¹ of P accumulates yearly in European soils (van Dijk et al., 2016), indicating the
5000 significant potential for P-recovery from this fraction. **An interesting TRL 6 STRUBIAS is**
5001 **to apply a pre-treatment to manure (e.g. moderate acidification, and the even more**
5002 **promising thermal hydrolysis technology) to increase the phosphate content of the**
5003 **liquid digestate from which the recovered phosphate salt will be precipitated.** At present,
5004 such technologies are already applied on manure in Europe, although the extent of occurrence
5005 in the year 2010 was still limited (Foget et al., 2011). In 2010, only 1377 t manure-P was
5006 acidified, whereas 665 t manure-P was subjected to thermal hydrolysis (Foget et al., 2011)
5007 but the combination of these techniques with P-precipitation has not yet been demonstrated in
5008 an operation environment.

5009 Sulphuric or other acids can be added prior to the digestion process to decrease the pH and
5010 shift the phosphate/total phosphorus equilibrium, and thus the P-recovery potential (up to
5011 80% of the total P present). However, careful consideration must be given to the soil and soil
5012 pH as application of acidic solid digestate will not always be acceptable, potentially limiting
5013 the large scale operation ability of this acidification pre-treatment. The thermal hydrolysis
5014 process is a high-pressure, high-temperature steam pre-treatment application for anaerobic
5015 digestion feedstocks. The feedstock is heated and pressurised by steam within a reaction tank
5016 before being rapidly depressurised (flushed). This results in the breakdown of cell structure
5017 within the biomass. As the organic matter is presented to the digester in a broken-down
5018 condition, the digestion process is more effective, resulting in increased gas production and
5019 improved digestate quality (Pell Frischmann Consultants Ltd, 2012). As such, the P-recovery
5020 efficiency could be increased from 13% to 50%, simultaneously optimising the N/P ratio of
5021 the solid digestate fraction. In case the pre-treatment process could be applied on manures
5022 that will be further processed by anaerobic digestion, an increase in P-recovery efficiency of
5023 13% to 50% would result in an additional recovery of **131 kt P yr⁻¹** (from 48 kt P yr⁻¹ to 179
5024 kt P yr⁻¹).

5025

5026 Another option to improve P recycling from manure is the use of manure incineration ashes
5027 as replacement for phosphate rock by the mineral fertiliser industry. The solid digestate
5028 fraction is combusted in order to achieve destruction of organic matter. If the moisture
5029 content within the digestate is sufficiently low and the incinerator efficiency is high, the
5030 process can become autothermal (the process generates sufficient heat to allow combustion to

5031 continue without the need for an external heat source or additional fuel) and energy recovery
5032 can be achieved (Pell Frischmann Consultants Ltd, 2012). Alternatively, the solid digestate
5033 fraction can be thermochemically treated in a rotary kiln by reaction addition (e.g. Si and/or
5034 Na₂SO₄; AshDec process) or pyrolysed. The char produced by the process can be used as a
5035 soil amendment or as a partial replacement for peat in growing media production.

5036
5037 **3. Fish residues** in Europe and Norway are still a largely unexplored P-source. As outlined in
5038 section 3.4.2, the P content of fish residues from catches and aquaculture for the EU-28 could
5039 amount of up to 27 kt P yr⁻¹. Moreover, the fish catches and aquaculture production in
5040 Norway equal about 45% of the total fish residues in Europe. Fish excreta and non-digested
5041 feed from land-based aquaculture also form a P-source that can potentially be recovered as
5042 STRUBIAS materials. The STRUBIAS sub-group indicated that these residues are already
5043 used for the production of P-fertilisers in Norway. Given that the characteristics of the
5044 protein fraction of fish residues are similar to those of terrestrial animal by-products, it is
5045 believed that fish residues could further increase the P-recovery potential in an indeterminate
5046 manner (up to 40 kt P yr⁻¹).

5047
5048 *8.2.10.3 Substitution effect*

5049 Results from the previous section will be used to estimate **the substitution effect of mined**
5050 **and synthetic fertilisers by fertilising products containing recovered phosphate salts,**
5051 **pyrolysis materials and ash-based materials for the year 2030.** This is based on the
5052 opening of the EU market, taking into account existing feedstock, the expected recovery rate
5053 and the equivalence of the fertilising features of recovered nutrients compared to those of
5054 mined and synthetic inorganic fertilisers.

5055
5056 The 2030 apparent consumption of synthetic and mined P-fertilisers is estimated at 1220 kt P
5057 yr⁻¹ (see section 8.1.3.2). By summing the values given in section 8.2.10.1, it is estimated that
5058 a total of 302 kt P yr⁻¹ could be recovered. **Hence, the substitution effect from STRUBIAS**
5059 **materials for the year 2030 is estimated at 25%.**

5060
5061 In case the **further market stimulations for sewage sludge and manure** as outlined in
5062 section 8.2.10.2 **would materialise**, the substitution effect for the EU-28 could increase to
5063 **40%.**

5064
5065 **In summary, it is estimated that the opening of the P-fertiliser market to STRUBIAS**
5066 **materials will result in a substitution effect of mined and synthetic fertilisers by**
5067 **fertilising products containing recovered phosphate salts and ash-based materials of 25-**
5068 **40%.** Moreover, it should be noted that pyrolysis materials have not been included in this
5069 assessment because an initial entry is considered more likely into the organic farming sector.
5070 The on-the-ground use of pyrolysis materials might enable the detailed testing of the
5071 agronomic efficiency of pyrolysis materials, possibly leading to more refined and precise
5072 estimates given in section 5.2.4. In case these results lead to increased market and consumer

5073 confidence for the use of these materials in conventional agriculture, the substitution potential
5074 will further increase.
5075

5076 **8.3 Market outlook for non-fertiliser PFCs derived from STRUBIAS materials for the** 5077 **year 2030**

5078 STRUBIAS materials – and more specifically ash-based materials and pyrolysis materials -
5079 can also be used in PFCs other than PFC 1 – fertilisers. STRUBIAS materials could be
5080 applied as liming materials, soil improvers, plant biostimulants, or as part of a fertiliser blend.
5081 Estimating a 2030 market for such fertilising materials is extremely challenging and
5082 associated with large uncertainties.

5083

5084 Question 6 to the STRUBIAS sub-group:

5085

5086 Please provide an outlook for STRUBIAS materials other than P-fertilisers, as well as their
5087 targeted PFC entry in the revised Fertiliser Regulation (i.e. liming material, soil improver,
5088 etc.). Please express numbers in absolute tonnes of material per year, and situate the numbers
5089 relative to the total PFC volumes applied in the EU-28 agricultural market. Also information
5090 on sales prices/gate fees of the end-materials is welcomed. More specifically, information is
5091 requested for following two materials:

- 5092 • C-rich pyrolysis materials in conventional agriculture, organic farming, and greenhouse
5093 farming (i.e. as a growing media);
- 5094 • Ashes generated by the forest-based industry, including the pulp and paper industry;

5095

5096

5097 **8.4 Conclusions on market potential for STRUBIAS materials**

5098 Based on the preliminary market assessment for the year 2030, significant market demand
5099 and trade is expected for all three STRUBIAS material groups in different segments of the
5100 EU agricultural sector. A stable legal framework for all three STRUBIAS material groups is
5101 desirable in order to provide a material quality benchmark for producers and consumers of P-
5102 fertilising materials containing STRUBIAS.

5103

5104

5105 **9 General conclusion**

5106 [to be completed for the final report]

5107

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5108 **10 Questionnaire**

5109 **10.1 Objective of the questionnaire**

5110 The objective of the questionnaire is to **validate** and, if necessary, **correct** and **complement**
5111 the techno-scientific information that provides the foundation for the proposed STRUBIAS
5112 material requirements outlined in this Interim Report. It is requested to **concentrate review**
5113 **efforts on the sections 5 - 8**, as your input on the sections 3 and 4 has already been taken
5114 into consideration when processing your feedback on the Background Document for the
5115 STRUBIAS Kick-off Meeting.

5116

5117 **10.2 Procedure**

5118 As outlined in the Rules of Procedure of the STRUBIAS sub-group, the sub-group member
5119 representatives shall actively collect information and deliver fact-based opinions on the
5120 questionnaires that form part of the written consultations. It is important that **STRUBIAS**
5121 **sub-group member representatives provide a consolidated opinion that is in line with**
5122 **the views of the member organisations and stakeholders they represent.**

5123

5124 Unfortunately, the JRC is not able to accept responses and opinions from organisations and
5125 individual persons other than official STRUBIAS member organisations and their selected
5126 representatives. The JRC recommends any third party organisations or persons interested in
5127 contributing to this work to contact one of the member organisations of the STRUBIAS sub-
5128 group⁵. These STRUBIAS members carry the full responsibility for the quality of the
5129 information sent to the JRC and may therefore decide to take any external input on board in
5130 their reply, or not, after careful consideration and thorough quality-checking.

5131

5132 The STRUBIAS sub-group members **shall support their opinions with objective and**
5133 **evidence based arguments**. In case of disagreement with the present proposals for nutrient
5134 recovery rules, sub-group members shall provide alternative proposals for alternative
5135 formulations along with supporting robust techno-scientific data and information.

5136

5137 Sub-group members shall use the channels provided by the Commission for discussion and
5138 information exchange. The preferential route for submitting non-confidential information is
5139 via the **CIRCABC platform** as this will facilitate a structured information exchange amid
5140 STRUBIAS members. Detailed instructions on how to access the CIRCABC STRUBIAS
5141 Interest Group were distributed to sub-group members via e-mail.

5142 Please upload any information in the folder/space entitled "Interim Report – Market study",
5143 and then select the matching sub-folders "Written feedback from sub-group". The document

⁵ The list of Members of the STRUBIAS sub-group can be found in the Register of Commission Expert Groups
→ Fertilisers Working Group (E01320)
(<http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetail&groupID=1320>)
→ Tab "Subgroups" → Subgroup of the Commission expert group on Recovery Rules for Fertilising
Products

5144 name should start with the acronym of the member organisation. Please note that all
5145 information that is uploaded in this CIRCABC folder is publically available. Techno-
5146 scientific literature can be uploaded in the corresponding sub-folder that is only accessible to
5147 STRUBIAS sub-group Members.

5148
5149 The JRC prefers to receive publically available information in order to support a transparent
5150 information exchange process. Nevertheless, it is accepted that some data cannot be made
5151 public and should be handled in a **confidential manner**. If only the data provider or data
5152 source is confidential, but not the data itself, it is desirable that member organisations
5153 anonymise the data provider/source and upload the document on CIRCABC as indicated
5154 above. Confidential data that cannot be publicly shared in any form should be sent via e-mail
5155 to JRC-IPTS-FERTILISERS@EC.EUROPA.EU. The document name should include the
5156 acronym of the organisation followed by the word "confidential".

5157
5158 The JRC is pleased to take into account any feedback on the questionnaire received from the
5159 STRUBIAS sub-group members until the deadline of Thursday 15 March 2018. We
5160 guarantee that any input received by the deadline will be taken into account for the further
5161 work.

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5163 **10.3 Questions**

5164 **Section A: General question**

5165 *A.1. Have you noticed any **incorrect or obsolete techno-scientific information** in the Interim*
 5166 *Report that has an important influence on the market for STRUBIAS materials? If your*
 5167 *observation involves an alternative proposal for the STRUBIAS material requirements,*
 5168 *please indicate, substantiate and upload supporting techno-scientific information.*

5169 Provide your feedback in a structured, tabular format with following headings: observation,
 5170 page/line numbers and section in the document, correction and/or alternative proposal,
 5171 techno-scientific rationale that supports the comment raised, reference to techno-scientific
 5172 data.

5173

observation	location in document	correction/ alternative proposal	techno-scientific rationale that supports the comment raised	reference to techno-scientific data
e.g. sales prices for mineral P-fertilisers are underestimated by 30%.	e.g. section 2.3.7.2 (line 2864)	e.g. sales prices vary from X to Y EUR	The data found in IFA report (2017).	e.g. IFA. (2017) has been uploaded on CIRCABC

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5175 **Section B: Specific questions and further data**

5176 Please note that all the queries of this section correspond to the questions given in specific
5177 sections of the document.

5178

5179 **Question 1 on sales prices of STRUBIAS materials on the market (section 7.1.3):**

5180 Please provide an indication of:

- 5181 a) the sales prices of STRUBIAS materials and mono-incineration ashes on the market
5182 (Euro per tonne material and P concentration, or Euro per tonne P; indicate if prices are
5183 "Free on Board (FOB)" or "CFR (Cost and Freight)" with an indication of the price for
5184 transport).
- 5185 b) Indicate also the physical form of the material (powder, granules, other relevant physical
5186 parameters), and to whom materials are sold (blending companies, retailers, end users,
5187 etc.).
- 5188 c) If available, please provide an evolution of the average sales prices in the last decade in
5189 order to determine the main factors affecting fertiliser price and their relative importance.

5190

5191

5192 **Question 2 on compliance costs (section 7.3):**

5193 Please provide information on the following elements that form part of the compliance costs:

- 5194 a) Cost for REACH registration for fertiliser end-material that will be brought on the
5195 market.
- 5196 b) Cost for compliance under already existing national end-of-waste or similar regimes
5197 that enable a market entry for fertilising products derived from STRUBIAS
5198 materials.
- 5199 c) Estimated cost for compliance for P-fertilisers derived from primary raw materials.
- 5200 d) For facilities that process waste-based materials, information on the cost associated
5201 to acquiring waste permits in different EU Member states for non-hazardous and
5202 hazardous waste materials. Notably, the costs associated to complying with the
5203 obligation for an establishment or undertaking carrying out waste management
5204 operations to have a permit or to be registered in accordance with Article 23-26 of
5205 the Waste Framework Directive 2008/98/EC.
- 5206 e) Cost of sampling and analysis through accredited laboratories:

5207 *Recovered phosphate salts:*

- 5208 - Nutrients: P, Ca, Mg, citric-acid P
- 5209 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn
- 5210 - Persistent organic pollutants: PAH16
- 5211 - Biological pathogens: E. coli or Enterococcaceae & Salmonella spp.
- 5212 - Others: macroscopic impurities, dry matter content, particulate matter < 100 µm.
- 5213

- 5214 *Ash-based materials:*
- 5215 - Nutrients: P, K, Ca, Mg, S, citric-acid P
- 5216 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn, B, Ba,
- 5217 Co, Mn, Mo, Sb, V
- 5218 - Persistent organic pollutants: PAH16, PCB, PCDD/F
- 5219 - Others: pH and neutralising value

5220 *Pyrolysis materials:*

- 5221 - Major elements: C, Corg, P, K, Ca, Mg, S
- 5222 - Metals and metalloids: As, Cd, Cr (total), Cr (VI), Cu, Hg, Ni, Pb, Zn, Ba, Co, Mo,
- 5223 Sb, and V
- 5224 - Persistent organic pollutants: PAH16, PCB, PCDD/F
- 5225 - Biological pathogens: E. coli or Enterococcaceae & Salmonella spp.
- 5226 - Other: pH, neutralising value, macroscopic impurities, particulate matter < 100 µm,
- 5227 particle density, volatile organic matter, specific surface area earthworm avoidance
- 5228 test (ISO 17512)

5229

5230 Where analysis packages are available (e.g. sampling + analysis of a series of

5231 metals, PAH16, PCB and PCDD/F), please clearly state what the package contains

5232 and its cost.

- 5233 f) Measurement standards currently applied (national standards, ISO/EN standards,
- 5234 etc.)

5235

5236 **Question 3 on possible economic benefits and drawbacks (section 7.4):**

5237 Please provide information, preferably in a quantitative manner, on following possible

5238 economic benefits and drawbacks of producing fertilising products containing STRUBIAS

5239 materials compared to equivalent mined and synthetic inorganic fertilising products.

- 5240 a) reduced waste compliance costs (e.g. changes in the economic valuation of sewage
- 5241 sludge ashes, etc.);
- 5242 b) reduced externalities (e.g. avoided costs due to eutrophication, positive effects on
- 5243 human health due to reduced contaminant levels, etc.);
- 5244 c) potential job creation in production and downstream fertiliser distribution and
- 5245 farmer's cooperatives; please relate expected STRUBIAS production volumes to
- 5246 number of persons employed.
- 5247 d) impacts on the rural economy;
- 5248 e) benefits of restoring soil organic carbon for soil fertility;
- 5249 f) cost associated to new logistics for recovered nutrient products;
- 5250 g) implications for the restructuring the production and distribution of fertilising
- 5251 products;
- 5252 h) agricultural equipment adaptations.

5253

5254

5255 **Question 4 on slags from the metallurgic industry (section 8.2.8):**

5256 Please provide an outlook for slags from the steel industry that are intended for use in
5257 agriculture. More specifically, information is requested on following aspects:

5258 a) Evolution in supply and demand for steel industry slags that are used as P-fertilisers in
5259 agriculture, as well a realistic outlook for the market outlook for the year 2030. Please
5260 express numbers in absolute tonnes of material per year, indicating the P concentration, or
5261 in kt P per year. Please provide separate datasets for different types of slags (blast furnace
5262 slag, basic oxygen slag, etc.).

5263 b) Data on the content of metals/metalloids (specifically B, Ba, total Cr, Cr (VI), Co, Cu,
5264 Hg, Mn, Mo, Ni, Pb, Sb, and V) in the different types of slag. Please provide full datasets
5265 or descriptive statistics indicating the 10th, 25th, 50th, 75th and 90th percentile of the
5266 distributions.

5267 c) At present, it remains unclear if the production process is adapted in order improve the
5268 quality of the resulting slag, or if any supplementary processing is performed on the raw
5269 slags obtained to increase their value as a fertilising material. Please provide any relevant
5270 information.

5271 d) Information on the relative agronomic efficiency of different output STRUBIAS
5272 materials.

5273 e) Evolution of the average sales prices of steel industry slags in the last decade and future
5274 outlook (Euro per tonne material and P concentration, or Euro per tonne P).

5275

5276

5277 **Question 5 on additional STRUBIAS pathways that should be considered for the 2030
5278 market assessment (section 8.2.9):**

5279 Please indicate any additional process pathways that result in the formation of P-fertilisers
5280 (pursuant definition and criteria of P-fertilisers as given for PFC 1 in the proposal for the
5281 Revised Fertiliser Regulation) and describe their market outlook in term of volumes of P that
5282 could be produced by the year 2030. The proposed pathways should meet following
5283 conditions:

5284 a) Derived from eligible input materials for each of the three STRUBIAS material groups as
5285 outlined in JRC Interim Report on nutrient recovery rules as distributed in May 2017 or
5286 derived from eligible input materials that were not listed, but are nonetheless in line with
5287 environmental and human health safety aspects and agronomic efficiency as indicated by
5288 techno-scientific evidence.

5289 b) Associated to a technological readiness level of stage 6-9.

5290 c) Realistic from an economic point of view based on the current and expected costs/gate
5291 fees for input materials, production processes, and revenues of generated output materials

5292

5293 **Question 6 on market aspects for STRUBIAS materials other than P-fertilisers (section**
5294 **8.3):**

5295 Please provide an outlook for STRUBIAS materials other than P-fertilisers, as well as their
5296 targeted PFC entry in the revised Fertiliser Regulation (i.e. liming material, soil improver,
5297 etc.). Please express numbers in absolute tonnes of material per year, and situate the numbers
5298 relative to the total PFC volumes applied in the EU-28 agricultural market. Also information
5299 on sales prices/gate fees of the end-materials is welcomed. More specifically, information is
5300 requested for following two materials:

5301 a) C-rich pyrolysis materials in conventional agriculture, organic farming, and greenhouse
5302 farming (i.e. as a growing media);

5303 b) Ashes generated by the forest-based industry, including the pulp and paper industry;

5304

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