Chapter 3
Circular Economy: Bridging the Gap Between Phosphorus Recovery and Recycling

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Abstract Circular economy for nutrients! How to transfer buzzwords into solid results? So far the potential to recover and recycle phosphorus remains untapped or is just inefficiently used as in the case of sewage sludge, manure and food waste. To provide alternatives to argued traditional nutrient recycling routes, various technical solutions have been developed in recent years. They allow recovery of phosphorus minerals suitable as raw material for industries like fertilizer production or even as ready-to-use renewable or next-generation fertilizer. This contribution focuses on mineral phosphorus-containing materials recovered from wastewater. It discusses legal aspects and market opportunities regarding their valorization in Europe. It has to be kept in mind that there are many other recovery/recycling options out there to allow sustainable nutrient management, especially when it comes to organic wastes and their recycling. A frequently updated inventory is provided on the European Sustainable Phosphorus Platform's website (http://www.phosphorusplatform.eu/). The current revision of the European fertilizer regulation within the European Commission's circular economy package provides a concrete example, what issues have to be coped with and what measures have to be taken to create a level playing field for both primary- and secondary-based materials destined for fertilizer use. Some EU member states have started to enforce phosphorus recovery from relevant wastes but are lagging behind in enabling efficient recycling, be it in mineral or organic form. Still, the so-called technical nutrient recovery is missing a demand-side driven market pull for recovered (secondary) nutrients and the biggest challenge will be bridging the gap between supply (recovery) and demand (recycling), especially when it comes to new types of materials or products, not already established on the market. Whereas in the past, the focus of nutrient recovery technologies was laid upon high recovery rates for single nutrients, now energy efficiency, synergies and cost become more and more important. What about value chains? We have to look for easy to implement rather integrative solutions instead of reinventing the wheel, creating fancy parallel (infra)structures.

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3.1 Introduction

Whether or not there will be a phosphorus (P) peak within decades, centuries or millennia (Cordell and White 2011; Scholz and Wellmer 2013), one thing is for sure – phosphorus is a limited and, in its function as a nutrient, an essential and irreplaceable resource (Asimov 1959). As Isaac Asimov stated in April 1959, in his essay 'Life's bottleneck', phosphorus limits the biomass potential on Earth. Essentially, all phosphorus in fertilizers and feed is originally mined from phosphorus-rich rocks, which are finite and distributed in just a few places on the planet. From the European perspective and in the light of having just one small mine in Finland, the geopolitics and economic vulnerability are issues to be taken seriously. Europe is highly dependent on phosphorus imports (de Ridder et al. 2012; van Dijk et al. 2016). Concerns about the reliability of global P data related to reserves, mining and processing capacities already led to several proposals to establish a global committee for independent monitoring (Wellmer and Scholz 2015; Acatech 2017).

Recovery and recycling can and have to play an important role in improving resource efficiency and sustainable nutrient management. Although both steps, recovery and recycling, are explicit stages in the European waste hierarchy, the legal framework as it is in place today still poses the impression to discriminate nutrients derived from secondary, renewable sources vs. primary sources.

On our way towards circular economy, traditional terms like waste, raw material and product deserve redefinition. Although nutrient recycling was well established and efficient without harm and low risk to human health and environment, industrialization, population growth and excessive mass production became a threat for those end points. In consequence and thanks to precautious thinking, waste criteria have been defined and implemented at the end of the last century. The implementation of regulatory barriers intended to reduce the distribution and circulation of hazardous substances from all kinds and fields of anthropogenic activity contributed to reduced water, soil and air pollution since the end of the last century. Also the prohibition of production and application of the so-called priority substances (chemicals considered threads to human health and environment) lead to improvements where implemented. Depending on the member state, either very fragmented or cross-environmental media approaches can be observed in the regulatory framework. The latter represent already a rudimental harmonization of requirements and restrictions for a certain set of environmental compartments (water, soil and air) – the integral approach.

Within the EU, there are two main levels of regulation: the European level and the member state level. Depending on the member state, there might also be provinces, federal states and even municipalities mandated to regulate certain issues. In general, one can state that the European level sets the general frame, and member states implement accordingly within certain flexibility, allowing stricter requirements, but not less strict requirements. Depending on type of EU level legislation, we distinguish between directives and regulations implementing the issues addressed in directives.

But the legal framework is only one side of the medal. To place a product onto a market also strongly, if not mainly, depends on non-legal criteria. It is always harder to find customers for new products, directly competing with a high-volume commodity or bulk market. Here new and better product properties, functionalities and performances that meet or even excel customer's expectations can play a key role. But also sufficient quantities and reliable supply, homogeneity, handling and other parameters are decisive. If quantities are rather limited, a niche market provides a good option for market implementation. If the product is tailored to enter an exclusive premium market, it is better to start there instead of trying to compete with a low- or medium-price market segment. It is much easier to lower sales prices, if the premium market uptake fails, than to increase prices once the product has been marketed for low or medium prices.

It makes a difference if the product is sold as a renewable, high-quality product or as waste-derived material with potential contamination and uncertain risks linked to the waste origin. I call these the opportunity-focused and the problem-focused marketing strategies. It is easy to conclude which strategy will be more successful. Some examples shall serve to provide more insights to the aspects briefly introduced.

3.2 The Legal Framework: Enabler or Disabler?

Before diving into details, it can be stated that any environmental protection measure would not have been implemented without law enforcement, especially when it's linked with additional cost. So, in general, it can be claimed that the legal framework, especially the environmental regulations, is a key innovation motor of our society.

Looking at Switzerland (2016) and Germany (2017), being the first European countries to really set and not just announce legal requirements for phosphorus recovery, an acceleration for P recovery technology development and implementation can be expected. Other member states already announced to follow the given examples of both. But, recovery alone is not yet recycling! Sure, there will be transition phases for implementation, but the clock is already ticking for the legislators to enable actual recycling.

The existing heterogeneity of legislation between the different 'domains' and between member states still poses barriers for EU-wide marketing of recovered nutrients. Even the recovery, when it comes to large-scale operations, as in the case of sewage sludge ashes, is hampered, since the border crossing transport of waste is very challenging from the operator's point of view. Here, initiatives or green deals like the North Sea Resources Roundabout (http://www.greendeals.nl/ north-sea-resources-roundabout/) can provide a good template on how these obstacles can be resolved on regional and multinational level.

Recycling and recovery are explicitly addressed in the five-stage waste hierarchy of the European Waste Framework Directive (2008/98/EC) setting the frame for all EU member states. The waste hierarchy is defined as follows, also setting the borderline between waste and non-waste status:

1. Prevention of waste	Non-waste
2. Preparing for reuse	Waste
3. Recycling	
4. Recovery	
5. Disposal	

Stage 1 represents the non-waste domain, whereas all other stages 2–5 represent the waste domain. Regaining product or end-of-waste status is the prerequisite for all materials to be allowed to be marketed in Europe as a product. The specific product or end-of-waste criteria for materials destined for a certain use are defined in the related regulations or ordinances. So, in the case of fertilizers, the European Fertiliser Regulation (2003/2003/EC), currently under revision, has to define the criteria for substances or materials to be used as fertilizers (PFC, product function category) or raw materials for fertilizer production (CMC, component material category). The European Commission follows the ambition to create a level playing field for both primary/virgin materials and secondary/renewable materials recovered from wastes. Although there are already various value chains established to enable the recycling of recovered nutrients, the implementation and interpretation of EU legislation can vary from member state to member state. Depending on the pragmatism of authorities, it can be observed that recovered materials allowed to be used as fertilizer or fertilizer raw materials in one member state can face a ban from this application route in another member state. Hopefully, this heterogeneity will be phased out after the revised EU Fertiliser Regulation entered into force. But this is not to be expected before 2019.

The national implementation of the Waste Framework Directive in Germany is the Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG), implemented in 2012. End-of-waste status in general is defined under Sect. 3.5:

1. The waste status of a material ends once having been processed/valorized and fulfilling the following basic requirements:

   (i) Being used for specific purposes.
   (ii) Has a market or demand.
   (iii) Meets all technical requirements for the intended application and complies with all legal requirements and standards for products (also implicating that it is registered under REACH).
   (iv) Its use does not lead to harm for human health and environment.

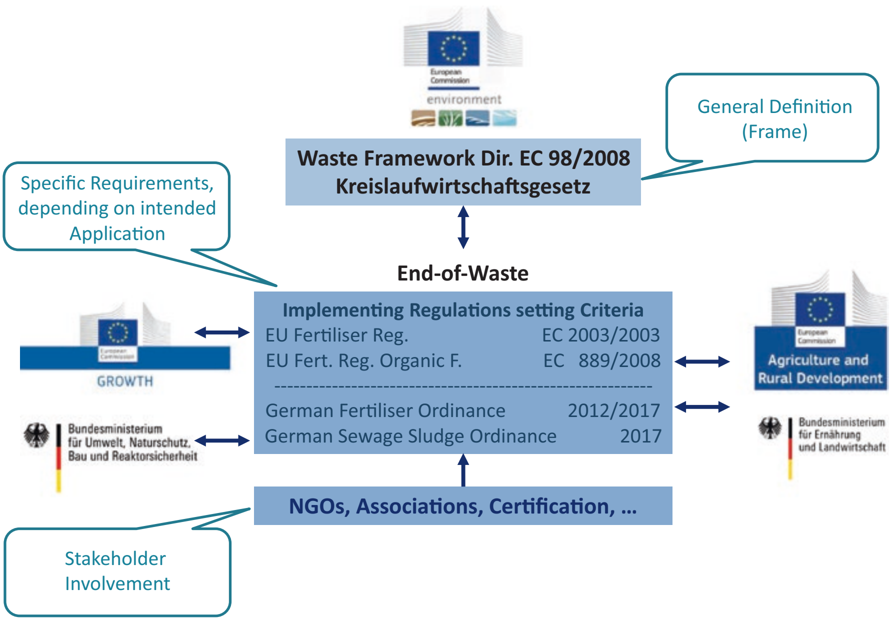

Fig. 3.1 Interaction of waste, fertilizer and sewage sludge regulation relevant for nutrient recycling in the EU and Germany

2. The federal government is mandated to define specific EoW criteria and implement specific ordinances after approval by the federal council including limit values for contaminants, etc. Both the sewage sludge ordinance and the fertilizer ordinance are such references.

Figure 3.1 intends to reflect the most relevant regulations for the valorization of recovered nutrients as mineral fertilizer. Table 3.1 provides an overview on contaminant limits set in different regulations or being currently under discussion for implementation. These are to be considered as part of the end-of-waste criteria. A big impact for recyclates, since most of them contain far less Cd compared to some fossil-based mineral phosphate derivates, can be expected from the implementation of cadmium limits under the EU Fertiliser Regulation. The European Commission's ambition is not only to introduce a Cd limitation but also to tighten the limit over the coming years. The starting point is intended to be set at 60 mg Cd per kg P_2O_5. It is still uncertain if and where the tighter limit will be set in the regulation after passing all political and juridical stages in the coming years, no matter if the EU still consists of 28 or 27 member states.

Most urgent is to set up the enabling framework allowing the fertilizer use for the following materials, representing the most prominent in the field of P recovery from wastewater/sewage sludge.

Struvite ($MgNH_4PO_4$ $6H_2O$) is the global champion in terms of quantity (several 10,000 tons) and number of installations (more than 40 operational) for mineral phosphates crystallized from the wastewater/sewage sludge stream. Similar to struvite, several Ca-based phosphates are recovered. Struvite as such is already mar-

Table 3.1 Legal requirements for sewage sludge and mineral recyclates

Parameters in mg/kg DM	EU municipal sludge framework dir. 1986	EU mineral fertilizer reg. draft 2016 PFC 1	STRUBIAS proposed PFC levels for inorg. macronut. fertilizer	Germany sludge ordinance		Germany Fertiliser Ord. 2012 last amended 2017
				1992	2017	
Heavy metals						
As – arsenic	–	60	60	–	–	40
Tl – thallium	–	–	–	–	–	1
Cd – cadmium	20–40	3	–	5/10	DüMV	1.5
Cd for P_2O_5 > 5%		60–40 mg/kg P_2O_5	60-40-20			50 mg/kg P_2O_5
Cu – copper	1000–1750	–	–	800	DÜMV	900
Hg – mercury	16–25	2	–	8	DÜMV	1
Ni – nickel	300–400	120	120	200	DÜMV	80
Pb – lead	750–1200	150	150	900	DÜMV	150
Zn – zinc	2500–4000	–	–	2500	4000	–
Cr – chromium (Total)	–	–		900	DÜMV	–
Cr – chromium (VI)	–	2	2			2

Organic compounds						
Organic carbon			3%			
PCB 28, 52, 101, 138, 153, 180 each				0.2	0.1	–
AOX				500	400	–
Benzo[a]pyrene				–	1	–
PAH_{16}			6?			
PFC (PFOA + PFOS)			tbc	–	DÜMV	0.1
I-TE Dioxins and dl PCB				0.1	DÜMV	0.03
(WHO-TEQ 2005)						
Biuret ($C_2H_5N_3O_2$)		1200				
Perchlorate (ClO_4^-)		1				

DÜMV fertilizer regulation

keted as fertilizer or can be used to customize the nutrient content, i.e. organic materials used as fertilizer or soil improver. Ca phosphates are mainly used as a fertilizer component.

P-rich incineration ashes, like from animal meat and bone meal, sewage sludge and other P-rich wastes, provide mineral concentrates, low or even free in organic contaminants suitable for fertilizer products (meeting CMC requirements) or even as fertilizer ready to use (meeting PFC requirements). Besides contaminant levels, the P availability for plant uptake will make the difference in case of ashes. Of course, as trends already indicate, the fertilizer route might not be the only one for ash-based materials, especially when considering merchant grade phosphoric acid or even white phosphorus (P_4), allowing valorization also in higher value markets.

A global inventory of installations has been recently published by (Walker 2017; Kabbe and Kraus 2017). The latter will be frequently updated and put online under www.p-rex.eu.

3.3 No Recycling Without Value Chains

Technologies to recover phosphorus from P-rich wastes like sewage sludge, ashes, manures and biowastes are already there (Schoumans et al. 2015; Kabbe et al. 2015; Ohtake and Okano 2015). Some of them are well advanced and already considerable as state-of-the-art, and others still need optimization not only in technical but also in economic terms. The major challenge will be the bridging of the gap between recovery and actual recycling (Fig. 3.2).

Closing the loop will only work with value chains. Otherwise, stockpiles of recovered nutrients will grow without being valorized. It also means that there needs to be customers for the materials recovered, be it for direct use as a product (fertilizer) or as raw material for further treatment and processing. Every processing step is linked with additional efforts (labour, energy, chemicals), finally meaning costs. The challenge will be, once the value chain is legally allowed to find customers, seeing the positive value in these materials and being able and willing to pay an adequate price. If the process chain fails to generate a positive value, only law enforcement can foster rather artificially a market for these recovered materials.

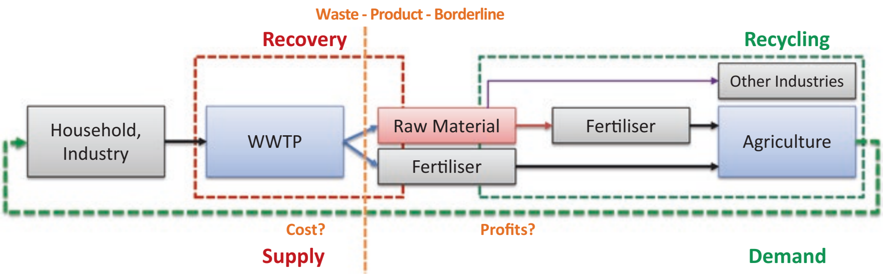

Fig. 3.2 Bridging the gap between phosphorus recovery and recycling – fertilizer value chain

The worst case would be that recovered materials end up as waste or that certain industries make profits by getting 'cheap' secondary raw materials in the end always heavily subsidized by the taxpayer. It's never the government; it's always us, who are paying taxes! Then of course a pressing question will arise: Is it more sustainable to invest in waste prevention instead of producing more and more waste that needs to be recycled? Still economic growth is kind of dogmatically linked with growing and exhaustive resource consumption. More and more stuff and waste are produced with less and less labour. Circular economy promises to make a difference, but so far, the so-called great transformation remains hidden behind the curtain, waiting for reasonable thinking to mature into reasonable action.

Technologies cannot be more than just one pillar to switch towards sustainable nutrient management and circular economy. Preventing waste is at least as important if not the most important approach. In the end, it is a societal challenge to define how and how fast we move forward and become circular.

3.4 Opportunities

Since not all value chains can be covered and discussed in this chapter and some of them are represented in other chapters, only the following may serve as a good example for the valorization of struvite.

Struvite has been recognized as an effective fertilizer providing the opportunity to reduce fertilizer consumption and nutrient losses to the environment. It is often called slow-release fertilizers. To reflect new functions or performance parameters overcoming the dogma of high water solubility, the term 'next-generation fertilizer' is becoming more and more popular. The following figure reflects how the Canadian company Ostara is bridging the gap between phosphorus recovery and recycling. A good technology and a good fertilizer product combined with a good marketing strategy are the key ingredients of Ostara success with already 14 recovery units up and running worldwide and recovered struvite sold as the premium fertilizer Crystal Green® (Fig. 3.3).

The combination of Ostara Nutrient Recovery Technologies' WASSTRIP and PEARL with LysoTherm in Amersfoort (NL, Waterboard Vallei en Veluwe) is one good example of the second-generation nutrient recovery with enhanced carbon management. Additional operational benefits besides prevented struvite scaling in the sludge train and reduced return load are improved biodegradation and increased biogas yield. The increased ortho-P concentration in the aqueous phase providing higher recovery rates and the reduced sludge solids to be disposed are strong arguments for implementation at WWTPs with enhanced biological phosphorus removal and anaerobic digestion. The operational cost can be reduced by several hundreds of thousands euros per year even without selling the struvite. Ostara's third installation in Europe just started operation in Madrid.

But, besides these operational benefits, Ostara's business case provides another selling point for potential customers. The offtake guarantee generates a source of

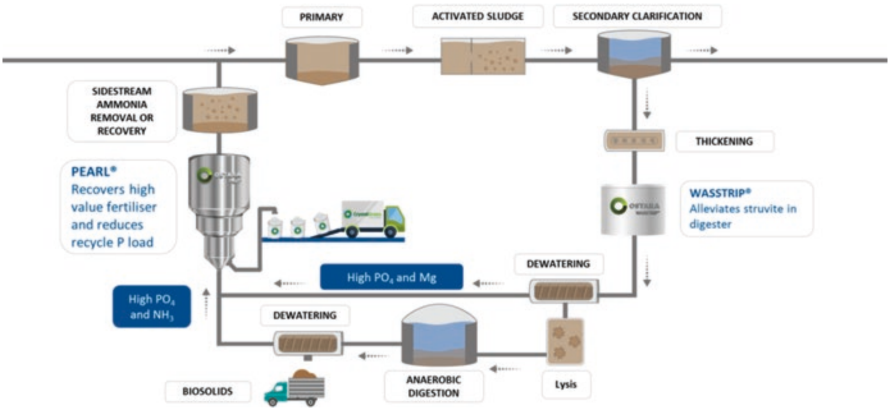

Fig. 3.3 Struvite recovery to recycling – the Ostara value chain (Source: Ostara)

Fig. 3.4 PEARL struvite recovery reactor and Crystal Green bagging station in Amersfoort (source: Kabbe)

income, since long-term contracts make sure the struvite produced on-site the WWTP will be taken off by Ostara and marketed as premium fertilizer Crystal Green®. Selling the Crystal Green® as premium product enables Ostara to pay their customers a reasonably good offtake price that is so far several times higher compared to other struvite valorizors. Since WWTP operators are often not familiar with fertilizer marketing and related bureaucratic burden, this business model provides a kind of appealing all-inclusive package (Fig. 3.4).

So it is not the technology alone that counts. Rather, the whole value chain has to be considered when deciding on a viable solution for nutrient recovery and reuse. Advantageously, struvite crystallization from wastewater also functions as a purification step. Struvite recovered in this way can even be classed as suitable for organic farming, the expert technical group on organic production (EGTOP 2016) has recommended.

3.5 Challenges

- The legal framework is tailored for existing structures and is very slow at adapting to future challenges. In relation to resource efficiency and sustainability, we are still a long way from implementing what is being discussed. For example, the upgrading of recovered material from being treated as a waste to being considered a resource or a product is proving to be a challenge with regard to legal barriers in place. The redefinition of end-of-waste criteria is a tough process but is a prerequisite to enable value chains to bridge the gap between recovery (supply) and recycling (demand) and make a circular economy really happen. Therefore, the revision of the EU Fertiliser Regulation (2003/2003/EC) needs to be progressed to provide a level playing field for fertilizers, irrespective of whether they are produced from fossil or secondary sources (Hukari et al. 2016). Another issue that deserves to be considered is the application of appropriate products for use in organic farming, for instance, by adding recovered struvite and calcined phosphates to the list of approved fertilizers in 889/2008/EC, as it was recommended by the Expert Group for Technical Advice on Organic Production (EGTOP 2016). Projects like the EU project IMPROVE-P (2013–2016) or the German project nurec4org (2017–2018) have been shaped to provide further fact-based information to facilitate stakeholder acceptance and cooperation along the relevant value chains from recovery to recycling.
- In some countries, decision-makers focus only on the 'highest hanging fruits' in terms of recovery and potentially recycling rates, instead of starting with the 'lowest hanging fruits' and allowing technical evolution. How can a market for material including P from secondary sources develop, if the already viable options are ignored and non-feasible options are favoured? A market starts with a product that is available and of use to someone. The same applies to the technology itself. Market penetration and replication will only happen with full-scale demonstrations. Instead of broadening the range of technologies, the focus should now be on setting up full-scale demonstrations of the most promising options. This should be augmented by making the most out of the existing infrastructure.
- If sludge incineration becomes the favoured or even only routed, the reason for improving the quality of wastewater and sludge will decrease, which can bear the risk that the sludge and finally ash quality will become poorer and poorer calling for increasing efforts to be taken for resource recovery. So far, the whole recov-

ery discussion is focused on sludge only, being an end-of-pipe approach. Wouldn't it be more reasonable also to trigger innovation upstream the WWTP or sludge train? What is the point to recover precious resources after having them contaminated?
- But also downstream of WWTPs, there is still potential to improve P recovery and recycling, just by applying better or more reasonable (authors avoid the term 'smart' here by purpose) sludge disposal or incineration logistics. As the German sewage sludge ash monitoring revealed, a big share of the German mono-incinerators burn municipal sludge mixed with industrial sludge. Why not exclusively dedicate the existing mono-incineration capacities for municipal sludge only? Instead of calling for more mono-incinerators, the decision-makers should foster first 'making the best and most out of the existing infrastructure'. This would save the taxpayer a lot of money and would prevent avoidable expenditures for surplus capacities.

3.6 Summary and Outlook

There is no doubt that phosphorus is a limited essential resource. Efforts should be taken to increase the resource efficiency of phosphorus while we have a choice. In the light of existing and feasible technologies, attention should be focused on bringing these to the market, rather than increasing the range of technologies. Also, the existing infrastructure already provides the opportunity to recover and recycle substantial quantities of P, including from ash. Smarter sludge management will help to make the most out of the existing infrastructure without the need for huge investments. Of course, recovery alone will not work. Feasible value chains are needed to bridge the gap between recovery and recycling. The current legal framework and the low prices for raw materials have to be considered as market barriers. At current price levels for phosphate rock and other raw materials, only legal requirements are likely to boost a widespread implementation of phosphorus recovery and recycling especially from the wastewater stream. A 'level playing field' is needed for fertilizers so that it does not matter if they are made from primary or from secondary sources. The definition of end-of-waste criteria for recovered nutrients is a crucial element, and binding recycling targets (comparable to the CO_2 emission reductions goals) based on achievable goals should be developed. The uncertainty-based precautionary dogma needs to be replaced by risk assessment-based requirements. Otherwise, no recovery technology and recycling value chain will be implemented in Europe if it is not providing benefits to its operators under current conditions. When it comes to data and their availability and reliability, we have to transform uncertainties into certain and fact-based knowledge. The future will be shaped by the ones who dare (to take a risk), not by the ones who fear! In the end only technologies yielding homogenous products or raw materials, independent from input material quality and meeting both criteria, energy efficiency and resource efficiency in unity, will have a chance for widespread application under sustainability aspects in a circular economy.

There is not only a lot of know-how already waiting to be shared with huge potential to be creatively transformed into innovation. Recovery to recycling value chains are already implemented here and there just waiting to be replicated. Think forward, act circular!

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