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frontiers | Frontiers in Sustainable Food Systems

TYPE Policy and Practice Reviews
PUBLISHED 04 August 2022
DOI 10.3389/fsufs.2022.937802

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 06 May 2022
ACCEPTED 14 July 2022
PUBLISHED 04 August 2022

CITATION
Duquennoi C and Martinez J (2022) European Union's policymaking on sustainable waste management and circularity in agroecosystems: The potential for innovative interactions between science and decision-making. *Front. Sustain. Food Syst.* 6:937802. doi: 10.3389/fsufs.2022.937802

European Union's policymaking on sustainable waste management and circularity in agroecosystems: The potential for innovative interactions between science and decision-making

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The European Economic Community (EEC) and later the European Union (EU) have issued policies on waste during the last 50 years. This paper aims at analyzing EEC and EU's policymaking on waste management and circularity in agroecosystems as compared with other sectors of waste management (e.g., municipal, industrial, construction waste, etc.). Even if founded on the same general principles, and especially the precautionary principle, policymaking on waste and by-product management in agroecosystems differs from waste management in other sectors. In particular, agricultural waste management has been excluded from the European Waste Framework Directive, from its start in 1975 to this day. The issue of waste and by-products in agroecosystems has been addressed in multiple Directives and Regulations, historically aiming at reducing the potential negative impacts of residual organic matter application in agriculture. In the last decade, the swiftly growing interest for circular economy has triggered a breakthrough in traditional waste management, potentially affecting all economic sectors and enforcing systemic perspectives rather than more conventional "silo" approaches. Circularity in agroecosystems should thus become a major subject of EU's policymaking, but may suffer from its lack of a general framework, contrary to waste in other sectors. Moreover, agricultural valorization of urban residual organic streams may face several roadblocks in between differing legislations for agroecosystems and for "non-agricultural" systems. A systemic approach of the question of residual matter in agroecosystems, backing a strong policymaking framework for the sector, would be necessary in this context. Science-policymaking interactions are necessary to tackle these issues and should take innovative forms to address their complexity. Policy briefs, Policy Labs and the new European Commission Scientific Advice Mechanism represent existing innovative tools to take the topic of policymaking for sustainable waste management and circularity in agroecosystems forward.

KEYWORDS

organic waste, agricultural waste, by-product valorization, waste management, circular economy, bioeconomy, policymaking, European Union

Introduction

According to European Union's official statistics (Eurostat), ∼2.3 billion tons of solid waste were produced in the EU in 2018, including waste from extraction, manufacturing and construction but excluding organic waste from agriculture and sewage sludge. Such figures are not so easily available for waste from agriculture and in this case are the subject of estimations resulting from diverse survey methodologies. Estimations vary also depending on the terminology used by the studies to qualify the considered residual material. In this article we will use the following definitions: "waste" means "any substance or object which the holder discards or intends or is required to discard" (Directive 2008/98/EC); "by-product" means "a substance or object resulting from a production process the primary aim of which is not the production of that substance or object" (Directive 2008/98/EC); "co-product" on the other hand is not the object of a EU definition and we will define it as "an intentional and unavoidable material created during the same manufacturing process and at the same time as the main product" (translated from Garcia-Bernet et al., 2020).

Bedoić et al. (2019) estimated at 18.4 billion tons the quantity of Agricultural wastes, co-products and by-products (AWCBs) produced in the EU between 2010 and 2016, representing a mean 2.6 billion tons/year, thus slightly exceeding waste quantity from all other sectors altogether. Eurostat estimated food waste, included in AWCBs by the authors of the latter study, at around 88 million tons (0.088 billion tons) in 2018. EU is considered contributing to <7% of the global food waste i.e., 1.3 billion tons per year as estimated by the United Nations' Food and Agriculture Organization (FAO). According to Lipinski et al. (2013) Europe (including Russian Federation) is the third contributor to global food waste (14% of global tonnage), on par with North America and Oceania (also 14%), far behind Industrialized Asia (28%) and South and Southeast Asia (23%) and followed by Sub-Saharan Africa (9%), North Africa, West and Central Asia (7%) and Latin America (6%).

Such amounts of residual organic matter represent both gigantic resource opportunities and potential risks for the environment and human health if not managed properly. From the 1970s on, the European Economic Community (EEC) and later the European Union (EU) issued policies on waste in the larger frameworks of environmental protection, sustainable development and, more recently, circular economy and bioeconomy. AWCBs are generally concerned by specific policies, substantially differing from other waste regulations, even if falling under the same general principles, such as the precautionary principle.

The transition from linear to circular economy is formally inscribed in EU's new Circular Economy Action Plan (European Commission, 2020) and reflected in several aspects of policymaking. Nevertheless, transitioning toward circular agroecosystems is far from direct and unchallenging, even if circularity is part of numerous farming traditions. We believe that transition to circular agroecosystems would greatly benefit from intensified interactions between science and policymaking, as it has been first pointed out by Bakan et al. (2022), and that these interactions should take innovative forms to address the subject's complexity.

In the following, we will present in Section The founding principles of European Union's environmental policymaking: how science has been challenged the founding principles of policymaking in the EEC and the EU, in Section From waste management to circularity: 50 years of European policymaking how these founding principles have been translated into regulation during 50 years of waste management policies. Section European policymaking on circularity in agroecosystems: from environment and health preservation to resource efficiency will be devoted to a more detailed account of policymaking on circularity in agroecosystems, along five dimensions: soil preservation, water quality, gaseous emissions, human health and resource efficiency. We will present in Section Actionable recommendations what we believe to be actionable recommendations toward renovated science-policymaking interactions and we will discuss in Section Discussion the potential for their application in the domain of sustainable waste management and circularity in agroecosystems.

The founding principles of European Union's environmental policymaking: How science has been challenged

Starting in 1973, the Environmental Action Programmes (EAP) have been designed to establish environmental legislation in Europe. The 1st EAP (1973–1976) was set up in response to emerging environmental concerns about scientifically established irreversible ecological damage and limitation of natural resources (Kiss and Sicault, 1972; Meadows et al., 1972; Rockström et al., 2009). The three principles enacted by the 1st EAP were (i) preventive actions, (ii) control/rectification at the source and (iii) the "polluter pays" principle (Thieffry and Nahmias, 1990). These principles were considered "innovative regulatory approaches to environmental policymaking" (Read and O'Riordan, 2017) and are still at the very core of European Environmental policymaking.

In parallel to these principles and underpinning them, the precautionary principle has been put at the center of European policymaking regarding the environment from the 1970s on (Read and O'Riordan, 2017) and the latter authors advocate that the European Union may be considered a forerunner and custodian of the application of the principle in its legal system. From the start, the precautionary principle as considered in the European environmental policymaking does not hinder innovation but rather regulates it. It ensures that political decisions are taken to the benefit of environment and public health protection whenever exists a substantial scientific uncertainty about risks associated with the considered innovation.

From the start, the precautionary principle thus heightens the need for strong interactions between scientific research and policymaking. The precautionary principle challenges scientific research at least (1) to rationalize what has to be considered as substantial uncertainty in a given context and (2) to increase knowledge and reduce uncertainty in specific fields (Kriebel et al., 2001).

From waste management to circularity: 50 years of European policymaking

Table 1 summarizes EU's policymaking timeline on waste management and circularity in general and, in parallel, in agroecosystems (as detailed in next part), enabling rapid examination.

According to Thieffry and Nahmias (1990), waste management was probably the most important domain addressed by the European environmental policy from the 1970s to the 1990s (from 1st to 4th EAP). Complementing the 1st EAP which consisted in resolutions (no obligation of application by the Member States), the European institutions issued the 1975 Waste Directive 75/442/EEC binding the Member States to apply it within defined deadlines. Furthermore, as a Directive, it enabled Member States to apply stricter measures as long as they respected the Treaty. The 1975 Directive in its original version consisted principally in an official definition of waste, in the translation of the 1st EAP's 3 principles in the field of waste management and in the obligation for the Member States to formally organize their national waste management system.

The 1975 Waste Framework Directive defined waste as "any substance which the holder disposes of or is required to dispose of [. . .]". It assorted this general and yet ambiguous definition with a list of 16 waste categories which were not based on the physical nature of waste (e.g., organic waste) but rather on their mode of production (e.g., "Q11: Residues from raw materials extraction and processing" or "Q15: Contaminated materials, substances or products resulting from remedial action with respect to land").

One important point of the 1975 Waste Framework Directive to keep in mind is that it explicitly excluded organic agricultural waste as well as wastewater from its scope. Later amendments of the Directive (successively 91/156/EEC, 2006/12/EC, 2008/98/EC, and EU 2018/851) carried on keeping wastewater and organic waste from agriculture out of their scope, leaving the field for specific legislation. Moreover, no Framework Directive concerning waste from and in agroecosystems in general has been issued but only specific ones. We will present them in more details in Section European policymaking on circularity in agroecosystems: from environment and health preservation to resource efficiency.

With the 4th EAP (1987–1992), a hierarchy of waste management principles appeared in 1989 (Gómez Palacios et al., 2002), putting prevention of waste production on top of the priorities, followed in decreasing order of priority by reuse, recycling, energy recovery, incineration without energy recovery and finally disposal. Near the end of the 4th EAP, Directive 91/156/EEC was the first to amend the 1975 Directive on waste and formally introduce the above-mentioned hierarchy of waste management strategies which is still effective.

Following the 1992 Rio Conference, the European Union established by the Maastricht Treaty put the concept of sustainable development at the core of its fundamental goals. In the following 5th EAP (1993–2000) waste management was one among 7 priority issues, namely climate change, acidification, urban environment, costal zones, water resources and biodiversity. During the 5th EAP, Decision 94/3/EC established a list of waste categories, once again according to their origin and not to their physical nature or composition. Category 02 has since then been devoted to waste (organic or not) from agriculture, horticulture, aquaculture, forestry, hunting and fishing. Other organic wastes may be found in category 03 (from wood and paper industry), 04 (from leather, fur and textile industry), 19 (from waste management industry including wastewater sludge, some composts, landfill leachate, etc.) and 20 (municipal waste including biodegradable waste). Decision 2000/532/EC used the 1994 categories as the base to define subcategories that are even more precise and, this time, are generally associated to the physical nature or composition of the residual materials.

TABLE 1 Timeline of European Union's 50 years of environmental policymaking on waste in general and on waste and by-products in agroecosystems.

Environmental Action Programmes (EAP)	Main orientations	General waste policy	Agroecosystems and waste policy
1st EAP (1973-1976)	Response to environmental damage. Introduction of 3 founding principles: (i) preventive actions, (ii) control/rectification at the source and (iii) "polluter pays" principle	1975 Waste Framework Directive (WFD), 75/442/EEC, excluding agricultural waste from its scope	
2nd EAP (1977-1981)			
3rd EAP (1982-1986)			1986 Sewage Sludge Directive (SSD). 86/278/EEC
4th EAP (1987-1992)	Introduction of hierarchy of waste management principles	1991 Amendement of WFD (Directive 91/156/EEC)	1990 Animal Waste Directive (90/667/EEC) 1991 Nitrates Directive (91/676/EEC)
5th EAP (1993-2001)	Introduction of sustainable development concept (1992 Rio Conference)	1994 Decision 94/3/EC: list of waste categories according to origin 2000 Decision 2000/532/EC: replacement of 1994 Decision with more precise subcategories	2000 Water Framework Directive (2000/60/EC) 2001 National Emissions reduction Commitments (NEC) Directive 2001/81/EC
6th EAP (2002-2013)		2006 Amendment of WFD (Directive 2006/12/EC) 2008 Amendment of WFD (Directive 2008/98/EC), including a definition of bio-waste	2002 Animal by-product Regulation 1774/2002 replacing 1990 Animal Waste Directive 2003 Fertilizing Products Regulation (FPR)2003/2003 2009 Amendment of FPR (Regulation (EC) No 1069/2009, Regulation (EC) No 1107/2009) 2009 Regulation (1069/2009) on animal by-products replacing 2002 Regulation
7th EAP (2013-2020)	Introduction of circular economy concept 2015 1st Circular Economy Action Plan 2020 New Circular Economy Action Plan	2018 Amendment of WFD (Directive 2018/851)	2016 Directive 2016/2284: replacement of NEC 2019 Amendment (Regulation (EU) 2019/1009) of FPR (including methanisation digestates)
8th EAP (2021-)			

With the dawn of the 21st century and 6th EAP (2002–2012) priority issues were reduced to 4: climate change, nature and biodiversity, environment and health, natural resources and waste. The issue of waste management was therefore linked to the preservation of resources into a "sustainable management of natural resources and waste" package, thus foreshadowing the future emergence of the concept of circular economy in European policies. During 6th EAP the Directive on waste was again amended by Directive 2006/12/EC and 2008/98/EC successively. One of the specificities of Directive 2008/98 was to introduce the possibility for some residual materials to exit the status of waste under given criteria, called End-of-Waste (EoW) criteria. Directive 2008/98/EC also introduced a definition of biowaste as biodegradable waste from agro-food industries, from the retail sector, from restauration and from households. The Directive promoted the separation of biowaste from other waste at the source, for further valorization by composting or anaerobic digestion (see Section "soil preservation").

The 7th EAP (2013–2020) saw the emergence of the circular economy concept and its implementation in EU's policymaking (Stankevičius et al., 2020). The 7th EAP was coupled with the 1st Circular Economy Action Plan (CEAP) introduced in 2015 (European Commission, 2015) and aimed at accelerating the transition from a linear to a circular model of economy. In 2018 the Waste Framework Directive was amended by Directive 2018/851, which is considered part of the Union's Circular Economy Package. Among others, it promoted the prevention of organic waste generation all along the food chain while especially targeting food waste and providing a definition for the latter. It also reinforced the separation of biowaste at the source.

The 8th EAP (2021-), as part of the European Green Deal adopted the objective of a "climate-neutral, resource-efficient and regenerative economy (which gives back to the planet more than it takes)." To achieve this goal, it has been identified that coordination among sectoral policies should be enhanced. Furthermore, environmental and climate concerns should underline a large amount of future European policymaking. On the same line of thought, and also part of the European Green Deal, the New Circular Economy Action Plan (nCEAP) adopted in March 2020 (European Commission, 2020) represents the new agenda for Europe's sustainable development.

European policymaking on circularity in agroecosystems: From environment and health preservation to resource efficiency

Organic wastes are produced at each step of the food chain. From "upstream" to "downstream" of the food chain, one can identify (adapted from Mérillot, 1998): waste and by-products of agriculture, waste and by-products of agro-food industries, waste from retail sector and restauration, household organic waste and finally excreta and/or organic waste from sewage treatment.

Waste and by products of agriculture fall into category "02 Wastes from agricultural, horticultural, hunting, fishing and aquacultural primary production, food preparation and processing" of European regulation (1994 Decision, see Section From waste management to circularity: 50 years of European policymaking). Starting with the 1975 Waste Framework Directive and throughout its subsequent amendments, organic waste from agriculture, as well as wastewater, were kept out of the Directives' scope, leaving the field for specific legislation. The principal rationale for this exception has probably to be related to the long history of the *in situ* reuse of farming organic residues, even questioning their status of waste: OECD's definition of waste prior to the Basel convention (1989) excluded "residuals directly recycled or reused at the place of generation" and thus did not consider organic residues reused at farm scale as waste (Pawelczyk, 2005). Manure especially has been considered as a fertilizer throughout the history of agriculture and probably from its starts as it has been evidenced for European Neolithic ages (Bogaard et al., 2013). In historical times record has been kept of the proven agronomical value of organic residues, largely viewed as resources for farming (Knittel, 2017) even after the spread of Liebig's theories and the dawn of industrial chemical fertilizers. It is therefore arguable that agricultural waste could not be included easily in the same policy as other categories of waste: the initial objective of European waste policy, and especially the 1975 Framework Directive, was to minimize disposal and promote recovery. The "back to soil" practice could be acceptably (even if controversially) considered as recovery rather than disposal.

Nevertheless, from the 1980s on, European policymakers had to face growing environmental issues related to the discharge of organic residues in soils and water from two main sources: the growing concentration of animal husbandry on one hand and the growing application of sewage sludge in agriculture on the other hand. The latter source inherited its growth from both urban development and stricter regulations on wastewater treatment leading to the growing production of sludge. The necessity appeared to apply the three principles of environmental actions (preventive actions, control/rectification at the source and "polluter pays") to organic waste from and in agroecosystems. Historically, governments have first focused on managing organic residues to reduce their impact on the environment and on human health, before tackling the issue of resource preservation. The following subsections describe European environmental regulations on the management of organic residual matter in agroecosystems, under five dimensions of constraints (soil preservation, water quality, gaseous emissions, human health and—more recently—resource efficiency) and in a rather historical perspective.

Soil preservation

Directive 86/278/EEC devoted to the use of wastewater sludge in agriculture and known as the Sewage Sludge Directive (SSD) was the first of specific Directives concerning waste in agroecosystems. In accordance with the precautionary principle, the main objective of SSD was the prevention of potentially harmful impacts of sewage sludge used in agriculture on soils, plants, animals and human health. The Directive enforced the treatment of sludge before its application and established concentration limits for heavy metals (Gómez Palacios et al., 2002). As a Directive, it has been complemented by stricter regulations in some of the Member States. Now considered as rather outdated, the SSD is under revision on the basis of new scientific knowledge about the risk associated with organic pollutants and pathogens as well as available sludge treatment technologies (Hudcová et al., 2019).

Except this Directive, there is no European regulation on soil protection to date. However, the idea is now more and more widespread that soil is a vital and largely non-renewable resource that has to be preserved as such. A European thematic strategy for soil protection, mentioned in the 6th EAP, has been issued in November 2021 (EU Soil Strategy for 2030, 2021), on the basis of a 2002 communication of the Commission (Communication COM 2002-179) It is expected to result in a legal initiative in 2023.

The question of how different organic waste fluxes, either from agriculture or from non-agricultural sources in the food chain such as sewage sludge or household organic waste, converge to being finally recycled in agroecosystems is a crucial issue for the sustainability of these waste management sectors. There have been for instance important debates in the 1990s about the "quality" of compost made from raw municipal waste, mostly around issues related to glass, plastics and heavy metal contents. Consequently, years 2000s saw a new scheme encouraging household waste sorting in order to isolate the organic fraction, labeled biowaste in Directive 2008/98/EC (amendment of the 1975 Waste Framework Directive). Biowaste separated at the source from other waste was thus to be transformed in a better quality compost for agricultural use. Besides composting, processes based on anaerobic digestion (AD) had a later expansion, first to produce energy in the form of biogas, then to reduce greenhouse gas (GHG). However, this trend of expansion of AD processes, which is still an urgent matter today, had also its limitation linked to the agronomic value of the digestates at the "end of pipe." One of these difficulties can be related to the diversity of waste mixes that AD plants may receive to optimize biogas production, leading to a variety of digestate compositions reflecting the variety of inputs. The adequation between digestate composition and the needs of the soil and crop system is therefore not automatically guaranted. The push toward biogas production, encouraged by national action plans and incentives, thus triggers new research needs in order to (a) define the status of the digestate and (b) provide references and guarantees pertaining to the agronomic value of its composition and to the safety of its utilization.

The Fertilizing Products Regulation (FPR) provides the framework for the application of organic by-products and waste in agriculture, excluding sewage sludge, which falls under the SSD. The first FPR was issued in 2003 (Regulation (EC) No 2003/2003) and successively amended in 2009 and 2019 (Regulation (EU) 2019/1009). Compost and digestate are listed among the materials allowed to enter the composition of fertilizing products, provided their compliance with requirements of the FPR.

Water quality

The quality of freshwater is affected by many human activities of which agriculture is one. Intensification of agriculture in the last decades has increased its proportion in water pollution. As agriculture is considered the greatest contributor to nitrate in European surface water and groundwater, many efforts have been devoted by EU policymakers to tackle the nitrate issue.

The 1991 Nitrates Directive (Council Directive 91/676/EEC "concerning the protection of waters against pollution caused by nitrates from agricultural sources") fixed a limit of 170 kg nitrogen per hectare for the amount of livestock manure applied to the land each year (including by the animals themselves). It aimed to protect water quality across Europe by preventing nitrates from agricultural sources to pollute ground and surface waters by promoting the use of good farming practices.

It has to be reminded that livestock manure also falls under the European Animal By-Product Regulations (see Section Human health).

Since its adoption on 12 December 1991, the nitrates directive is implemented through the establishment of action programmes particularly within Nitrate Vulnerable Zones on a compulsory basis. Moreover, every 4 years the Member States are required to report on the Nitrates concentration in groundwater and surface waters. Thus, the European policy pressure on nitrates has been undoubtedly maintained and even increased. The last report on implementation of Nitrates Directive (Communication COM/2021/1000) issued in 2021 takes note of the lowering of water pollution in the EU related partly to the decrease in N fertilizer consumption in the Union. It also underlines the need to better take into account the rise of digestates from anaerobic digestion as a new source of nutrients and to assess their impact on water quality. This trend will be addressed in the Integrated Nutrient Management Action Plan to be issued by the Commission in 2022.

The Nitrates Directive forms an integral part of the water framework Directive. More extensive, the Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council) laid the foundations for a new policy on water quality, integrating all previous regulations regarding specific water pollutions or specific quality standards. For instance, though reinforcing the Nitrates Directive, it abrogated the 1976 directive on dangerous substances discharged into the aquatic environment (Directive 76/464/EEC) and its daughter directives, based on an approach by substance. More precisely, the Water Framework Directive defines a framework for the elaboration and the implementation of water policies in the European Union, institutes general objectives and principles, but do not contain any operational measure beyond the existing regulations.

River Basin Management Plans are the key tools for implementing the Water Framework Directive. They are drawn up after extensive public consultation and are valid for a 6-year period. The plans for 2022–2027 represent the second cycle under formal Water Framework Directive obligations.

Gaseous emissions

Ammonia

In Europe, agriculture is responsible for over 95% of ammonia emissions (Giannakis et al., 2019). Livestock production represents about three quarters of these, coming from manure storage and spreading, and animals housing and grazing.

The best-known environmental effect of ammonia emissions is its contribution to the acidification of sensitive ecosystems (forests, lakes…). Another environmental effect of nitrogen deposition, spread on a wide scale across Europe, is the eutrophication of natural ecosystems, leading to biodiversity loss. Ammonia (NH_3) and nitrogen oxides (NO_x) are both sharing this responsibility.

The Gothenburg Protocol (1999) fixed national annual emissions targets for different gases: NH_3, SO_2, NO_X and volatile organic components (VOC), to be reached by 2010. On this basis, the 2001 National Emissions reduction Commitments (NEC) Directive (Directive 2001/81/EC of the European Parliament and of the Council) fixed national emissions ceilings for the same different gases, to be reached for the same year and, for ammonia, at the same level as the Gothenburg Protocol. Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants is the main legislative instrument to achieve the 2030 objectives of the Clean Air Programme (European Commission, 2013). The Directive entered into force on 31 December 2016, repealing Directive 2001/81/EC 2 on national emission ceilings for certain atmospheric pollutants, with effect from 1 July 2018. An overview of the extent to which Member States meet their respective emission ceilings is made available by the European Environment Agency (European Environmental Agency Website on Air Pollution).

Greenhouse gases

Greenhouse gases (GHG) emissions attributed to agriculture represent an estimated 12 Gt CO_2e/y (CO_2 equivalent per year) in 2019 among global anthropogenic GHG emissions estimated at 52 Gt CO_2e/y (IPCC, 2019). According to the same source, the principal GHG emission categories and respective proportions (in CO_2e) by agricultural systems are: 43.3% CO_2, 37.5% CH_4 and 19% N_2O.

CO_2 emissions result principally from land use and its changes (Moran and Wall, 2011) and in a lesser measure from the on-farm use of fossil energies and the manufacturing of inputs (Dollé et al., 2011). The latter authors underline that CO_2 from animal respiration as well as plant metabolism should be considered biogenic and therefore that only CO_2 emissions from fossil energies and manufacturing of inputs should be accounted for in anthropogenic additions to the greenhouse effect.

At the European level, CH_4 emissions come for one third from manure management and two-thirds from enteric fermentation of ruminants (cattle for the main part). Livestock production is responsible for 45% of N_2O emissions from the soil, taking into account indirect emissions linked to atmospheric deposition and nitrogen leaching and run-off (European Environment Agency, 2005). CH_4 and N_2O together, livestock production counts for three quarters in GHG emissions from agriculture.

The global warming issue has been addressed, from the regulatory point of view, quite similarly as the atmospheric pollutants problem. The well-known Kyoto Protocol (United Nations, 1998) was adopted in December 1997, during the third session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC).

The European Climate Law (Regulation (EU) 2021/1119) fixes the objective for the EU of reducing GHG emissions by at least 55% by 2030 compared to 1990 emission levels and to reach climate neutrality by 2050.

Human health

Because of the risk of disease transmission from animals to humans, animal by-products (ABPs) are the subject of specific regulations. ABPs are defined as any non-edible matter of animal origin: skin, bones, horns, blood, fat, bodies of animals died on farm, manure, guano, egg shells, feathers, etc. as well as the animal part of food waste (meat, milk, cheese, eggs, etc. non-suitable for human consumption). ABPs are the subject of European regulations since the sanitary crisis of transmissible spongiform encephalopathy (TSE) starting at the end of the 1980s. The first Animal Waste Directive 90/667/EEC was successively replaced by Animal By-Product Regulation (EC) 1774/2002 and more recently by 1069/2009/EC. According to it, APBs are classified into three categories:

Category 1 is composed of material presenting the highest risk of transmissible disease (especially TSE) and which should be incinerated or recycled as fuel product only. Category 2 consists in APBs presenting intermediary sanitary risk and which can be valorized as fertilizer, biogas or compost, provided the minimization of pathogens and contaminants in the process; manure falls into category 2. Category 3 is the one including material presenting the lowest risk and which can be used as feed for livestock provided preventive measures to avoid pathogen transmission in the human food chain are strongly enforced.

Resource efficiency

This last dimension is to be distinguished from the preceding ones because it deviates from "classical" waste management and relates more to circular bio-economy. Regulation (EU) No 1305/2013, one of the declinations of the Common Agricultural Policy (CAP), promotes agriculture as a supplier of renewable sources of energy as well as organic wastes and by-products for the bio-economy (Garske et al., 2020).

Circular bio-economy

EU issued its first bioeconomy strategy in 2012 and updated it in 2018, identifying five major objectives: (1) "ensuring food and nutrition security," (2) "managing natural resources sustainably," (3) "reducing dependence on non-renewable, unsustainable resources," (4) "mitigating and adapting to climate change, (5) "strengthening European competitiveness and creating jobs" (European Commission, 2018). The 2018 strategy is translated into a plan consisting in 14 actions. These actions are clearly transversal and generally not specifically dedicated to agro-ecosystems with only one of them mentioning "sustainable food and farming systems, forestry and biobased products."

Nevertheless, the bioeconomy strategy was translated to agroecosystems through research projects of EU's Horizon 2020 framework program. Many of these projects are to be related to the concept of biorefinery. Biorefinery is often placed at the heart of bioeconomy, since it encompasses all ways of processing biomass into bio-based products and bioenergy (International Energy Agency's definition of biorefinery). The innovative concept of environmental biorefinery (Moscoviz et al., 2018), also known as waste biorefinery is particularly investigated in the context of circularity in agroecosystems.

For example, and just to mention a few projects, incentives to reduce food waste by 50% at the 2030 horizon triggered, among others, innovations to convert food waste into livestock feed as an alternative to soy-based products (NOSHAN project, started in 2012, grant agreement n° 31214). The SYSTEMIC project (Grant Agreement n° 730400) demonstrated technologies to recover mineral nutrients from waste streams (manure, sewage sludge, food waste) to produce soil improvers and fertilizers. The AGRIMAX project (grant agreement n° 720719) developed a cascade process to convert waste and by-products from the culture of fruits and cereals in Spain and Italy into added-value molecules, fibers, biogas and fertilizers. The BIOrescue project (grant agreement n° 720708) created an innovative biorefinery concept converting compost from mushroom production into high-valued products such as bio-pesticides, biodegradable nano-carriers for drug encapsulation and horticultural fertilizers.

Water resource recovery

The recovery of municipal or industrial wastewater as a resource, known as Wastewater Reuse (WWR), is a major issue in today's agroecosystem, especially when considering circularity. Water reuse is not a new technique or concept; knowledge on wastewater treatment and reuse has been accumulated along with the history of humankind (Angelakis et al., 2018). WWR is mainly performed in regions suffering water scarcity (e.g., the Near East, the Middle East, Mediterranean countries, Ait-Mouheb et al., 2018). It has greatly increased in the last years in Europe (especially in Spain, Italy, Cyprus and Malta) but it remains negligible in other South European countries (Portugal, France, countries of the former Yugoslav Republic, Albania and Bulgaria) and moderate elsewhere (Greece with Crete Island, in Renault et al., 2014). The European Commission insists now that the subject is no longer confined to southern Europe but may concern all EU nations. Nevertheless, despite EU incentives and the inclusion of this option in the bioeconomy strategy, there is insufficient integration of the reuse concept in EU's global water policy: "reuse is more complicated, more costly and perceived as more risky" (Doeser, 2017), in particular concerning the risk on human health. Close to Europe, Israel has achieved the highest rate of water reclamation in the world.

The precautionary principle applies fully regarding the subject of wastewater reuse. It triggers the necessity to increase scientific knowledge and reduce uncertainty. Several European research projects are in progress on such treatment systems as intensifed treatment wetlands, to develop compact systems able to reach pathogen removal objectives for reuse, compare different low cost final stage disinfection technologies for rural areas or using soils for final disinfection stage before reuse. Technical solutions are being developed to allow this flexibility of treatment methods and develop adapted irrigation devices and practices. One example of such dedicated projects is MADFORWATER, a research and innovation project funded by the European Unions's Horizon 2020 programme (Grant Agreement n° 688320).

Actionable recommendations

As first stated in our introduction, we strongly advocate that transition to more circular agroecosystems would greatly benefit from intensified and, above all, renovated interactions between science and policymaking on the subject.

Of course, scientists are only part of multiple stakeholders involved in policymaking, together with policymakers, lawyers, economic actors, NGOs and the general public. Nevertheless, the role of scientists is very specifically devoted to produce neutral knowledge. Thus, organization of the scientific advisory process in general is deemed particularly important in a time when controversies are numerous and sometimes rough, whether within the scientific community itself or with other stakeholders.

The complexity of environmental issues requires innovative interdisciplinary scientific approaches, some of them aiming at objectifying political choices, for example by developing multicriteria approaches or adapting and combining cost-benefit analysis (CBA) and Life Cycle Analysis (LCA). Innovative scientific methodologies are necessary to answer such questions as: how to take into account health impacts in these multicriteria/systemic approaches? To what extent does current negative perception of some technologies or strategies (e.g., wastewater reuse, see Section Water resource recovery) affect political choices? How to open structured dialogue spaces *via* innovative consultation approaches?

Over the last few years, one could witness several advances in the way scientific advice can be embraced by the decision-making process. We identified three existing innovative instruments in which the overall subject of organic waste and by-product management and circularity in agroecosystems could be better addressed:

- The first instrument, policy briefs, may be the better known by the scientific community as well as policymakers today.

- More recently, Policy Labs have also emerged as an innovative instrument of co-construction between policymakers and other stakeholders.
- Lastly the European Commission implemented renewed processes of science-policymaking interactions, such as the Science Advice Mechanism (SAM) and the Knowledge4Policy (K4P) platform, which can be considered a set of innovative and promising instruments.

Policy briefs

By definition (Smith, 2015), a policy brief is a concise summary of a particular issue, the policy options aiming to deal with it, and some recommendations on the best option to take. It is addressed to government policymakers and other stakeholders who are involved in formulating or influencing policy. Under different possible formats, policy briefs are a key tool to present research and recommendations to a non-specialized audience. They serve as a vehicle for providing evidence-based policy advice to help readers make informed decisions. A strong policy brief distills research findings in plain language and draws clear links to policy initiatives. It is commonly produced by scientists in response to a request formulated directly by a decision-maker or within an organization that intends to advocate for the position detailed in the brief. A policy brief might synthesize the same scientific findings than a research paper, but it will deploy them for a very specific purpose: to help readers decide what they should do. It will relate the findings to current policy debates, with an emphasis on applying the research outcomes rather than assessing the research procedures. A research paper might also suggest practical actions, but a policy brief is likely to emphasize them more strongly and develop them more fully.

Several policy briefs have been issued in the domain of waste management and we will only quote a few of them hereafter. For instance, Bourguignon (2015) authored "Understanding waste management policy challenges and opportunities" under the auspices of the European Parliament Research Service. This 10 page brief is an executive summary of main waste management issues and the differences between EU countries. It compares the share of options like composting, anaerobic digestion, incineration, landfilling and material recycling and identifies current challenges, like the promotion of recycling, as well as opportunities in terms of economic benefits. A more recent policy brief released by the Economic Research Institute (Kojima et al., 2020) emphasizes the negative impact of the COVID-19 pandemic on waste management (increase of plastic waste, protection needed for informal workers, etc.) and points out the need for a fast adaptation of waste management systems.

Lemaire and Kerr (2016) provide another example of policy brief within the course of a project entitled "Waste management: innovative solutions for African Municipalities." This brief is therefore more orientated toward increasing awareness on the emerging critical issue of urbanization in developing countries and the huge volume of waste being therefore produced by municipalities. It focuses on proposing policy recommendations for local governments of Sub-Saharan Africa.

Policy briefs are becoming a regular output of EU projects, like the ones being posted within the Policy Learning Platform (https://www.interregeurope.eu/policy-learning-platform) on the topic of "Environment and resource efficiency" (March 2020, Interreg Europe).

We would therefore recommend a growing production of policy briefs in the field of sustainable waste management and circularity in agroecosystems, for example as outputs of EU projects, as well as, more generally, a greater promotion of their publication in individual and collective evaluation of research.

Policy labs

Policy Labs have been promoted as structures providing innovative processes for the dialogue between science and policymaking. By definition, Policy Labs are dedicated teams, structures, or entities focused on designing public policy through innovative methods that involve all stakeholders in the design process. Practitioners describe these efforts as design or evidence-based approaches, which places the end users at the center of each stage of the policy-making process. After proposals are formulated, they are tested and validated through various forms of experimentation.

Although rather recent in their development and implementation, Policy Labs are already the subject of various reviews trying to analyze their pros and cons (Lewis, 2021). Other authors (Wellstead, 2020) see Policy Innovation Labs (PILs) as a global response to the growing demand for public sector innovation and the development of policies addressing complex issues. Policy Labs are definitely in vogue, and it is more and more thought that they have an important part to play in the generation of innovative solutions for policymaking, although *per se* they will not be able to solve every societal challenge.

In European Union's Member States, public Policy Labs are described as emerging structures constructing public policies in an innovative design-oriented fashion, in particular by engaging citizens and companies working within the public sector (Fuller and Lochard, 2016). This latter publication reports the EU's survey to identify the best Policy Lab practices. The study identified various categories of Policy Labs including some dedicated to ≪ Resource Efficiency, circular economy and waste ≫. One of the most prominent is SITRA, a Finnish public fund based in Helsinki that established the world's first national road map to a circular economy in 2016. The road map, updated in 2019, plotted Finland's route to achieving a circular economy by 2025. This Policy Lab is providing information to the public through tools and methods as well as expertise to the Finnish government. In France, "Bretagne Creative" was launched in

2012 to identify and promote examples of social innovation and transitions. It works as a network and has been editing a magazine for 7 years.

Other examples of Policy Labs described in the EU's survey are mostly organizations sustained at city-level and dedicated to specific solutions, e.g., the Gdynia Innovation Center, Silesia, Poland; the Barcelona Urban Lab, Catalonia, Spain; The Cornwall council, Truro, England, UK; the PDR User Lab, Cardiff, Wales, UK; the innovation Lab, Belfast, Northern Ireland, UK. The EU's survey emphasizes the fact that Policy Lab managers play a key role in selecting projects for which an experimental approach will generate meaningful insights and outcomes. It also exposes that Policy Labs operate at various levels of government (from municipalities to national government) and that they are mostly based on a systemic approach that therefore transcends administrative silos.

Nevertheless, it is notable that the scientific community is generally not widely involved in Policy Labs. We advocate that renewed dialogue between science and society, as well as between science and policymaking and between policymaking and society, would altogether beneficiate from a greater involvement of the scientific community in "extended" Policy Labs. It is our opinion that the overall subject of circular bioeconomy, and more specifically of circularity in agroecosystems, would be a notable "candidate" for multipartite experimentations in Policy Labs. Nevertheless, this increased involvement should not bear on the sole initiative of individual researchers but rather should be coordinated by scientific collectives (research institutions, learned societies,...).

Innovative EU's science-policymaking interactions

The innovative European Commission's Science Advice Mechanism (SAM) was created in 2016 to replace the Chief Scientific Advisor who was until then the sole scientific advisor, reporting directly to the President of the European Commission. The SAM is based on an expert Group of Chief Scientific Advisors, at this date composed of 7 leading scientists nominated by the European Council. It is underpinned by the Science Advice for Policy by European Academies (SAPEA), a consortium of 5 European Academy Networks (Academia Europaea, All European Academies, European Academies' Science Advisory Council, European Council of Applied Sciences and Engineering, Federation of European Academies of Medecine) representing all the scientific disciplines, from humanities to engineering and the different member states. The SAM mission is to issue Scientific Opinions on key topics to establish or expand policy and legislation. SAPEA and the Group of Chief Scientific Advisors closely collaborate on the production of these Scientific Opinions, together with invited experts and stakeholders, following an overall process schematically described in Figure 1. To date, 18 topics have been addressed by the SAM, 4 of them being directly related to agroecosystems (glyphosate in 2016, agricultural biotechnology in 2017, plant protection products in 2018 and sustainable food system in 2020).

In 2018, the European Commission's Joint Research Center (JRC) launched its Knowledge4Policy (K4P) platform consisting in an online searchable database and 20 "knowledge centers" on specific topics such as bioeconomy, global food and nutrition security and territorial policies. These centers are designed to "make accessible relevant scientific information, bring together scientists and policymakers, communicate available evidence and enhance the knowledge base" on each specific domain. The JRC itself is clustered in 10 "science areas" covering more than 50 "Research Topics." The subject of waste management and circularity in agroecosystems falls naturally in the "Environment, resource scarcity, climate change & sustainability" cluster and encompasses a large spectra of subjects such as "Resource management," "Sustainable production and consumption and the circular economy" and "System understanding of resources and climate" to name a few.

Short synthesis of actionable recommendations

It is our overall recommendation to intensify the integration of innovative science-policy interactions in research projects in the domain of circular bioeconomy in general and circularity in agroecosystems in particular. This challenging goal could be achieved through:

- A growing production of policy briefs as outputs of EU projects,
- Valuable incentives to increase the involvement of researchers in Policy Labs,
- A greater promotion, through positive evaluation, of researchers' involvement in innovative science-policy interactions in individual and collective evaluation of research,
- A strong involvement of scientific collectives (research institutions, learned societies, ...) in these innovative instruments. The increased involvement of the scientific community in science-policy interactions should not bear on the sole initiative of individual researchers and should in no case be detrimental to their knowledge production activity.

Discussion

To date, and to our knowledge, the particular field of residue management and circularity in agroecosystems has not yet been the subject of any innovative form of interaction between science

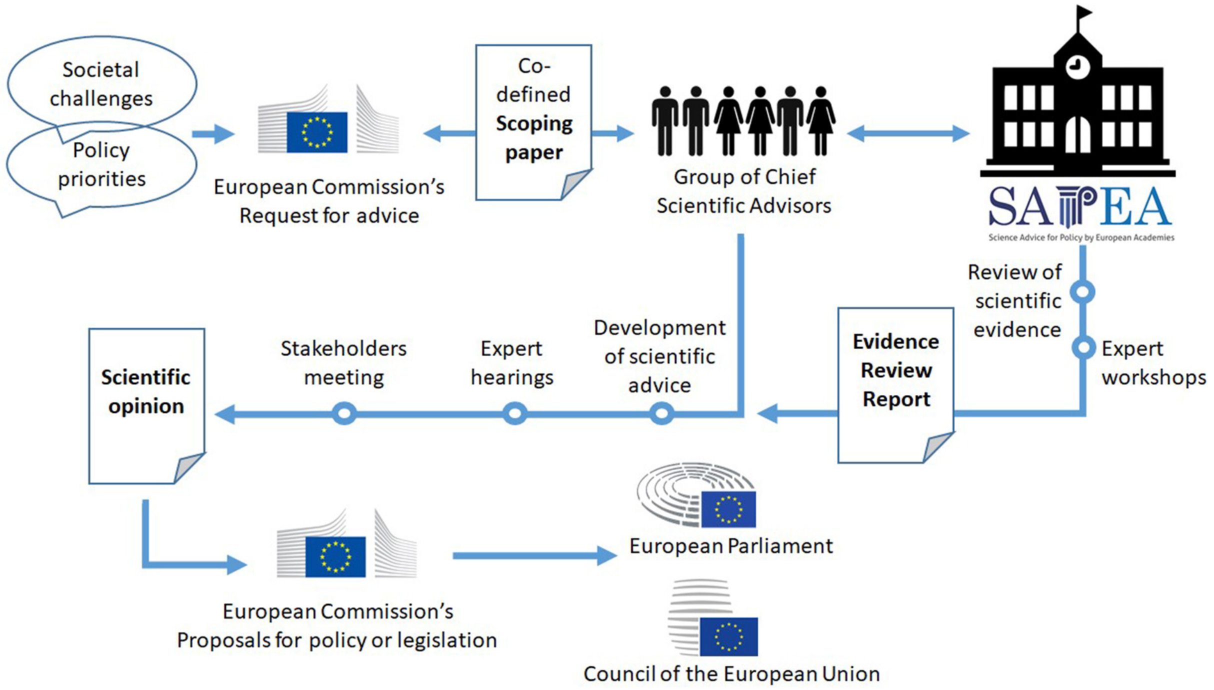

FIGURE 1
Simplified process of the EU's Science Advice Mechanism (SAM), adapted from https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/scientific-support-eu-policies/group-chief-scientific-advisors_en.

and policymaking, whereas waste management and circularity in other systems have been addressed by policy briefs and Policy Labs. On the other hand, subjects related to agroecosystems but not specifically related to waste and circularity have also been dealt with by sets of innovative interactions and the subject of 4 Scientific Opinion reports by the EU's Science Advice Mechanism (SAM).

It is our opinion that this absence has to be mainly related to the lack of a strong policymaking framework for the corresponding topic of Agricultural wastes, co-products and by-products (AWCBs) and more generally the valorization of residual matter in agroecosystems. As we have already stated, related issues are tackled by specific policies largely pertaining to the impact of organic residues on what could be considered as independent compartments of the environment and of human health.

Therefore, it is also our opinion that the systemic aspect of the question of residual matter in agroecosystems has been to date neglected by policymakers and would greatly beneficiate from innovative interactions between scientists and policymakers. This could be done through policy briefs and/or Policy labs. Sustainable waste management and circularity in agroecosystems could also find a place in EU's innovative forms of scientific advice, for instance in the above-mentioned Knowledge4Policy (K4P) platform already including "bioeconomy" in its Knowledge Centers. The systemic concept of "sustainable circular bioeconomy" could be an interesting unifying framework for innovative forms of interactions between science and policymaking on sustainable waste management and circularity in agroecosystems.

Author contributions

CD and JM designed the study. CD brought expertise from the field of general waste management and JM from waste management in agroecosystems as well as policy support. CD wrote the article with input from JM. Both authors approve the submitted version.

Acknowledgments

The authors wish to thank the reviewers for their attentive amendment of the article and their insightful comments.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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