Original Article

wm&r

Waste Management & Research
31(12) 1262–1278

DOI: 10.1177/0734242X13507968
wmr.sagepub.com
SAGE

Review, mapping and analysis of the agricultural plastic waste generation and consolidation in Europe

Demetres Briassoulis[1], Epifania Babou[1], Miltiadis Hiskakis[1], Giacomo Scarascia[2], Pietro Picuno[3], Dorleta Guarde[4], and Cyril Dejean[5]

Abstract
A review of agricultural plastic waste generation and consolidation in Europe is presented. A detailed geographical mapping of the agricultural plastic use and waste generation in Europe was conducted focusing on areas of high concentration of agricultural plastics. Quantitative data and analysis of the agricultural plastic waste generation by category, geographical distribution and compositional range, and physical characteristics of the agricultural plastic waste per use and the temporal distribution of the waste generation are presented. Data were collected and cross-checked from a variety of sources, including European, national and regional services and organizations, local agronomists, retailers and farmers, importers and converters. Missing data were estimated indirectly based on the recorded cultivated areas and the characteristics of the agricultural plastics commonly used in the particular regions. The temporal distribution, the composition and physical characteristics of the agricultural plastic waste streams were mapped by category and by application. This study represents the first systematic effort to map and analyse agricultural plastic waste generation and consolidation in Europe.

Keywords
Agricultural plastics, agricultural plastic waste, waste generation, waste consolidation, plastic waste composition

Introduction

An extensive and steadily expanding use of plastic films in agriculture, and particularly in protected horticulture, has been reported worldwide since the middle of last century. The term 'plasticulture' refers to the practice of using plastic materials in agricultural applications. The plastic materials are oftentimes and broadly referred to as 'agricultural plastics'. Some of the reported benefits of using plastic materials in agricultural fields result from increased yields, earlier harvests, less reliance on herbicides and pesticides, frost protection and water conservation. The use of agricultural plastic has also provided a more efficient use of farm land, higher quality of crops and a resultant healthier environment. Furthermore, plastics-based agricultural systems provide effective solutions to crop growing in many ways: in arid regions, for example, plastic piping/drainage systems can cut irrigation costs by one to two-thirds, while as much as doubling crop yield (Levitan and Barros, 2003; Plastics Europe, 2011). In southern Europe, the majority of the agricultural plastic concerns agricultural films for protected cultivations, while in northern Europe the majority of the agricultural plastic concerns silage films and direct cover films (Taiganides, 1979). Agriculture today involves very modern materials and technology, as can be seen from the brief review that follows.

Conventional plastic films

Conventional plastic films are mainly polyethylene (PE)-based films, but there is also some polyvinylchloride (PVC) used, as well as films made from speciality polymers. Polyethylene is the main material of the agricultural plastic films used by the majority of growers because of its affordability, transparency, durability, strength, flexibility and easy manufacturing. The raw materials are usually low-density PE (LDPE), and ethylene-vinyl acetate (EVA) or ethylene-butyl acrylate (EBA) copolymers for the covers and linear low-density PE (LLDPE) for mulching (Espi et al., 2006). In 2010, the European plastics industry produced 57 millions tonnes of plastic, or 21.5% of world production. Five percent of this volume, or a little more than 2.8 million tonnes of plastic, was destined for agriculture. LDPE film alone accounts for approximately 60% of the production of all agricultural plastic—approximately 502,000 tonnes (APE Europe, 2012). The main applications are silage; wide flat films for silos; stretch films for wrapping bales;

[1]Agricultural University of Athens, Department of Natural Resources and Agricultural Engineering, Athens, Greece
[2]DISAAT Department, University of Bari, Bari, Italy
[3]SAFE School, University of Basilicata, Potenza, Italy
[4]GAIKER Centro Tecnológico, IK4 Research Alliance, Parque Tecnológico, Zamudio, Spain
[5]IRSTEA (Institut National de Recherche en Sciences et Technologies Pour L'environnement et L'agriculture), Montpellier, France

Corresponding author:
Demetres Briassoulis, Agricultural University of Athens, Iera Odos 75, Athens, 11855, Greece.
Email: briassou@aua.gr

greenhouses; and high and low tunnel films used to protect horticultural cultivations from harsh climatic conditions in different seasons. Microclimate parameters may be controlled inside greenhouses and high or low tunnels (exploiting the specially designed radiometric properties of the films) to achieve high productivity and shift the regular production period, while integrated pest management and organic cultivations can be introduced efficiently. The properties of these LDPE-based films are usually modified by special additives to control the plant growth, soil temperature and water losses, weeds and insects, to offer ultraviolet (UV) stabilization, incorporate anti-drip/anti-fog behaviour, infrared (IR) opacity, UV-blocking, and near IR (NIR)-blocking while fluorescent, and ultrathermic films have also been developed (Dilara and Briassoulis, 2000; Espi et al., 2006; Hemming et al. 2006; Kittas et al., 2012; Kumar et al., 2009).

Moreover, if their design follows certain specifications, they provide important advantages with respect to their functionality (von Elsner et al., 2000). It was found that new cool plastic films having special cover properties of NIR reflection during the day and far IR reflection during the night maintained a favourable microclimate for crop growth in tropical regions.

Mulching film conserves water, controls soil temperature and economizes on use of herbicides (Espi et al., 2006; Laverde, 2002).

Biodegradable plastic films

Because of the difficulty in recovering the conventional polyethylene mulching film after its use, biodegradable films have been developed and commercialized. These are films (usually made of bio-based materials) that, after their use, can be buried in the soil along with the plant remains to be decomposed by microorganisms. Biodegradation should leave no toxic substances in the soil or other undesirable by-products, and should be fast enough so as not to result in accumulation during the consecutive cultivation periods. Biodegradation or biotic degradation is chemical degradation of materials (e.g. polymers) brought about by the action of naturally occurring microorganisms, such as bacteria, fungi and algae (Gross and Kalra, 2002; Kyrikou and Briassoulis, 2007; Nayak, 1999). As biodegradation proceeds it produces carbon dioxide and/or methane and water, minerals and a new biomass. If oxygen is present the biotic degradation that occurs is aerobic and carbon dioxide is produced. If there is no oxygen available, the biotic degradation is anaerobic and methane is produced instead of carbon dioxide. Under some circumstances both gases are produced. The ‘biodegradability’ of plastics depends on the raw materials, and the chemical composition and structure of the final product, as well as on the environment under which the product is expected to biodegrade (Leja et al., 2010).

The development of new grades of bio-based biodegradable in soil mulching films represents a challenging research area associated with an attractive market (Martin-Closas and Pelacho, 2011).

Photo- or thermo-degradable films

Polyethylene films containing as additives special pro-oxidants are commercialized as degradable for various applications (including degradable mulching films). These films degrade into very small fragments under solar radiation (UV) and/or heat. It is claimed that the degradation fragments (or a portion of these fragments) can be assimilated by soil microorganisms. This is a highly controversial issue as these plastics have not succeeded in meeting the biodegradability specifications of any standard test for biodegradation, while there are open questions on the fate of the remains and on possible irreversible pollution of the agricultural soil (Briassoulis and Dejean, 2010; Grima et al., 2001, Kyrikou and Briassoulis, 2007).

Plastic nets

The use of nets has been introduced the last few decades in agriculture as protected cultivation covering and for other applications. The industrial production of agricultural plastic nets in Europe is steadily expanding. For example, in Italy, more than 5300 tonnes of nets made of high-density PE (HDPE) is produced for agricultural applications per year. Permeable covers are extensively used in certain types of cultivation, such as fruit-tree farming, and for hail, bird and insect protection. Moreover, nets are used as insect-protecting screens along greenhouse ventilation openings and shading screens above greenhouse roofs, and for the last few years, nets are being used in the place of strings on round bales. In these applications, agricultural nets support the production of lower-input products using lower levels of agrochemicals and, in some cases, reducing or eliminating the need for energy consumption. In this respect, plastic nets are considered as an environmentally- and human health-friendly alternative to pesticides. Agricultural nets not only contribute to increased production, but they also have a positive effect on the quality of the produce by mildly moderating the microclimate under the cover. Nets can also be used to shift the regular production period in order to increase the market value of the produce and distribute more evenly the availability of fresh high quality products over an extended period of time. Nets are also used for protection against adverse climatic action (Castellano et al., 2008).

Irrigation pipes

An irrigation system is usually used to assist in growing crops in dry areas and during periods of inadequate rainfall. Additionally, irrigation also has a few other uses in crop production, which include protecting plants against frost, suppressing weed growth in rice fields and helping to prevent soil consolidation. Drip irrigation tubing consists of hoses specifically designed to carry and drip water slowly into the soil exactly at the plant root zone, where it is needed. This way, moisture levels are kept optimal, improving plant productivity and quality. Most pipes used in irrigation systems today are plastic pressure pipes made of HDPE and medium-density PE, or PVC or cross-linked PE owing to their ease of installation and resistance to degradation.

Fertilizer bags

Fertilizers are widely used in the agricultural fields. They are chemical compounds applied to promote plant and fruit growth, and are usually applied either through the soil (for uptake by plant roots) or by foliar feeding (for uptake through leaves). Fertilizers can be placed into the categories of *organic fertilizers* (composed of decayed plant/animal matter) or *inorganic fertilizers* (composed of simple chemicals and minerals). These compounds are packaged in special fertilizer sacks that are usually composed of LDPE, HDPE or polypropylene (PP).

Agrochemical packaging

Agrochemicals, particularly the liquid ones, are packaged in plastic containers. The main material used is HDPE or HDPE with a thin internal layer of a barrier film [(e.g. polyamide (PA)] to ensure impermeability.

Agricultural plastic waste

The plastics used in agriculture constitute approximately 2% of the total plastics consumed in Europe per year, generating about 700,000 tonnes of waste per year (EUPC, 2007) and 4% in the USA. Despite their low share, their use is concentrated geographically within Europe in certain agricultural areas of high productivity. This presents a problem, but also an opportunity. A problem of overloaded pollution and an opportunity because they can be easily consolidated and processed if an appropriate waste management system is established. In addition to this, each agricultural plastic waste (APW) category has a very homogeneous composition, rendering the waste stream very valuable to the recycler.

A relatively small portion of the agricultural plastic waste is recycled, but this varies widely from country to country and at regional level. The majority of agricultural plastic waste is either buried in the soil or burned uncontrollably in the fields, or discarded infields, and most of it ends up in landfills. Burying of these materials in agricultural land represents an imminent threat for irreversible soil contamination, degradation of soil quality characteristics and, possibly, for the safety of the food produced in such fields (Briassoulis et al., 2010). Furthermore, accumulated plastic film residues in soil can cause significant decreases in yield (Ren, 2003).

Furthermore, uncontrollable burning of agricultural plastic in fields is extremely frequent, releasing harmful substances, with the associated obvious negative consequences to the environment and human health, and possible danger for the safety of the food produced in such fields, with negative commercial impact (Briassoulis et al., 2010). More particularly, agricultural plastics burn easily, but incompletely, in an open-burning scenario. Incomplete combustion can lead to the release of particulate matter, carbon monoxide and sulphur dioxide, as well as many other air pollutants. In addition, hazardous by-products can be present in the residual ash and in airborne emissions in the form of heavy metals, dioxins and furans. The emissions of greatest concern during open burning of agricultural plastics are probably dioxins and furans, which are particularly formed in instances of low combustion temperatures, such as those associated with open burning (Andreasen and Fitz, 2006; Sonnevera International Corporation, 2011). Dioxins and furans are a health concern, even in very small quantities, being associated with endocrine disruption, heart disease, and cognitive and motor disabilities, as well as being a known human carcinogen (Sonnevera International Corporation, 2011). Humans can be exposed to dioxins directly by breathing or through the skin, or through plants or meat, as they concentrate in animal fat. This suggests that the burning of agricultural plastics, and associated dioxin generation, is particularly troubling, as the practice occurs on or near active agricultural land. Further, if the majority of dioxin intake to humans comes from food sources, dioxin emissions from the burning of agricultural plastics has the potential to affect a wide population when they land on feed crops and are concentrated in the bodies of farm animals. It is characteristic that burning 4536kg of agricultural plastic has the potential to contaminate 75,000 kg of soil from exposure to dioxins, based on Canadian Soil Quality Guidelines (Sonnevera International Corporation, 2011).

Another group of pollutants of concern emitted from the burning of plastic agricultural waste are polycyclic aromatic hydrocarbons (PAHs). PAHs are considered pollutants that have the potential to have a widespread effet on the environment (Mumtaz and George, 1995; Sonnevera International Corporation, 2011).

The consequences of the disposal of agricultural plastic waste in fields and landfills include aesthetic pollution and landscape degradation of regions of natural beauty and tourist areas, threats to domestic and wild animals, blocking of water flow through water channels or pollution of the sea, and overload of landfills with an immediate environmental and financial impact (Briassoulis et al., 2010). Many of these degraded plastic fragments end-up in the sea, polluting the sea water and threatening sea organisms.

All these practices are illegal based on the Landfill Directive (Directive 99/ 31/EC), which forbids the uncontrolled burying of the waste, the Incineration Directive (Directive 2000/76/EC), which states that uncontrolled burning is prohibited, and the Revised Waste Framework Directive (Directive 2008/98/EC), which forbids uncontrolled discarding. The legal framework underlying agricultural plastic waste has been studied and is presented in detail in Liantzas et al. (2007). Despite this legislation, every year tons of agricultural plastic waste are burnt or uncontrollably disposed to the environment. However, the European legal framework states:

> In accordance with the ‘polluter pays’ principle, the cost of disposing of waste must be born by (Directive 2008/98/EC):

Table 1. Applications of plastics in agriculture around Europe (LabelAgriWaste data).

Protected cultivation films	Nets	Packaging	Silage	Piping, irrigation/ drainage	Other
Greenhouse	Anti-hail	Fertilizer sacks	Silage films	Water reservoir	Bale twines
Low and high tunnel	Anti-insect	Agrochemical containers	Bale wraps	Channel lining	Bale wraps
Mulching	Wind break	Tanks for liquid storage	Silage bags	Irrigation pipes	Nursery pots
Nursery	Shading	Crates		Drainage pipes	Strings
Direct covers	Anti-bird			Micro-irrigation	Ropes
Soil decontamination	Nets for olive- and nut-picking			Drippers	Hydroponic substrate sacks, spiral wrapping, bags, tools, sacks, containers, etc.
Shading					

- the holder who has waste handled by a waste collector or by an undertaking contractor and/or

- the previous holders or the producer of the product from which the waste came.

The lack of an agricultural plastic waste management scheme in most European countries, or the inefficiency (technical and/or economic) of existing schemes (with a few exceptions, usually applicable to certain categories of agricultural plastic waste), also facilitated by the lack of a European scheme for APW, is the main reason why the farmers, with the pathetic acceptance of the local authorities, apply the above illegal practices to disposing of their APW.

According to statistics, APW accumulates in the environment at a rate of 25 million tonnes per year worldwide (Orhan and Buyukgungor, 2000). Disposal of wastes, therefore, must be done in such a way and at such a rate that nature will assimilate the wastes and recycle them into resources (Taiganides, 1979).

The serious environmental problems related to the management of APW at the European level led to the European research project *LabelAgriWaste* (‘Labelling Agricultural Plastic Waste for Valorising the Waste Stream’), aimed at developing an economically viable scheme for the collection and valorization of APW destined for recycling or energy recovery. After completing a study of existing schemes (for APW and for other waste streams), and a study of the existing legal framework and the legal tendencies, a labelling scheme for APW was designed, tested and improved through a series of pilot tests (Briassoulis et al., 2008 a,b, 2010; Hiskakis and Briassoulis, 2006, Hiskakis et al. 2008).

The current research was conducted in the framework of *LabelAgriWaste* aiming at offering a detailed geographical mapping and analysis of agricultural plastic use and waste generation and consolidation in Europe, focusing on the areas of high agricultural plastics concentration. Quantitative data and analysis of the agricultural plastic waste generation by category, geographical distribution, and compositional range, and physical characteristics of the agricultural plastic waste per use and the temporal distribution of the waste generation are presented. This work represents the first systematic effort to map and analyse APW generation and consolidation in Europe.

Analysis of APW generation in Europe

Qualitative characteristics and categories of APW in Europe

Table 1 summarizes the main categories of agricultural plastics and their most important applications around Europe (*LabelAgriWaste*). Some applications (i.e. the plastic trails for the packing and transport of the agricultural products to the market) have not been considered in Table 1 because the end user is the merchant and not the farmer.

South Europe. Spain and Italy are the two major consumers of Agricultural Plastic Products (APP) in Europe. In southern Spain and Italy, they consume, in particular, films for protected cultivations (greenhouse covering, medium/low tunnel films and mulching films) because they contribute to the qualitative and quantitative increase of production. Also, temporary coverings of structures for fruit trees, vineyards, and vegetable, ornamental and floricultural cultivations using films or nets are found in Italy. Other manufactured plastics are used in the form of irrigation and drainage pipes, silage films, pots for ornamental plants and flowers, nursery containers, soilless culture substrate, bags, and containers and tools. In France, the main field applications are greenhouses, small tunnel and mulching films, spiral wrapping, silage film, unwoven direct cover, woven PP nursery film, other plastic products, strings, pipes, drippers, tapes, big-bags, sacks, containers, pots and nets. The main categories of agricultural plastic products found in the Greek market include greenhouses, high and low tunnels, mulching and nursery films, silage, bunker silo-covering films, films for soil disinfection, agricultural nets, irrigation pipes and drippers, fertilizer bags and containers for agrochemicals. In Cyprus, farmers usually make use of mulching films, low tunnel and greenhouse films, irrigation pipes, nets and bale wrap films, and bags and containers. In Portugal the prevailing plastic product categories used are protected cultivation films.

North-central Europe. In north and central Europe the main categories of agricultural plastics are crop cover films, silage films and bale wraps, and, to a lesser extent, mulching and greenhouse films. In the UK and Ireland the main categories of agricultural plastics are crop cover films, silage films and bale wraps, while in Germany are direct covers, mulching and silage films, bale wraps and nets are the main categories. In Finland bale wraps, silage films, nursery pots and greenhouse films are the main categories of agricultural plastics. In Belgium, in the Netherlands and Hungary greenhouse, low tunnel, mulching and silage films, as well as hydroponic sacks substrate and spiral wrapping are widely used in the agricultural sector. In Poland and Romania the prevailing plastic product categories are mulching, low tunnel, greenhouse, direct cover films and also silage films. Plastic covers are also used in Latvia and Czech Republic. Finally, in Scandinavian countries (Denmark, Norway, Sweden), silage films are widely used in fields (*LabelAgriWaste*)

Composition of APW

In general, the composition of the majority of the agricultural plastic films is LDPE that, in several applications, may contain EVA or EBA copolymers. Greenhouse film materials are usually polystromatic with three layers. Also, LLDPE is common in low-tunnel films and, in some cases, in mulching films. HDPE is mainly used in the production of irrigation pipes and containers of agrochemicals, and for bale wraps and agricultural nets. PVC is used in some cases in the production of irrigation tubes. PP is used in several countries, especially for strings, bags, twines and, in a few cases, for specific nets (nonwoven layers). Also, some polycarbonates, PA, polyethylene terephthalate and polymethyl methacrylates are used. The natural and synthetic rubbers used in tyres also constitute an important volume of polymer used in agriculture (Brown, 2004).

Chemical additives are also used in the structure of agricultural polymeric materials in small quantities, aimed at imparting special properties to the various films and other plastic products, depending on the application. A compound may contain up to 15% of its weight in additives and up to 15 different additives. Some of the most commonly used families of additives are slip and anti-blocking, antioxidants, UV absorbers, light stabilizers, anti-dripping or surface tension modifiers, and additives that block far-IR, pigments, photoselectives and other fillers. Frequently, more than one additive from a single family is used. These additives are more or less complex chemical molecules with different properties, some of them acting synergistically.

Additives used to protect transparent films against ageing induced by UV radiation are various forms of hindered amine light stabilizers, possibly combined with UV absorbers to achieve synergetic results, while nickel-quenchers are not used widely any more owing to the environmental impact of nickel. Carbon black is an economical additive for UV protection of the black-coloured mulching films and irrigation pipes and tapes. Other types of additives used include anti-fog and anti-drip agents, IR-absorbing mineral fillers for the regulation of the greenhouse heat balance (or, alternatively, use of polymeric materials with intrinsic IR-absorbing properties), diffused light transmission providing mineral fillers, energy-absorbing dyes or pigments, or photo-selective reflecting pearl pigments and others (Briassoulis et al., 2004; Dilara and Briassoulis, 2000).

Table 2 shows the range of chemical compositions of the main agricultural plastics per type of APP that is found in the majority of the European countries.

Another category of agricultural plastics is the category of agricultural biodegradable plastics. There are no official statistical data available so far on the use of biodegradable plastics in Europe, mainly because of the early state of the market development of these materials. Most figures available are estimations resulting from the BP (European Bioplastics, 2011) manufacturers. Biodegradable mulching film, 12–20 μm thick, is the main commercial biodegradable agricultural plastic produced from biodegradable in soil materials. Mater-Bi (based on starch complexed with biodegradable polyesters) is one of the commercial materials used for biodegradable mulching films in Europe (Briassoulis 2004, 2007; Novamont, 2013). New biodegradable materials and new grades of existing materials are developed and appear in the market of the biodegradable mulching films (Martin-Closas and Pelacho, 2011; Martin-Closas et al., 2008; Rudnik and Briassoulis, 2011). It should be clarified here that a material may be considered to be 'biodegradable in soil' if it can be shown beyond any doubt that it is fully and environmental safely degraded and assimilated by microorganisms under special conditions (e.g. in soil for mulching films) within a reasonable timeframe (defined by standards) so as to avoid accumulation due to consecutive uses (Briassoulis and Dejean, 2010). The result of the biodegradation is the formation of water, carbon dioxide and/or of methane, and of minerals and a new biomass, leaving no toxic elements for the environment and any remains or fragments (Briassoulis and Dejean, 2010; Kyrikou and Briassoulis, 2007). Other biodegradable products (strings, soil solarization films, films to cover little tunnels, ornamental plants, and flower pots and nursery containers) are still in an experimental phase, so they are not yet commercialized. Also, the first ever experimental biodegradable irrigation thin wall pipes and rigid pipes with drippers have been developed recently at experimental level (Hiskakis et al., 2011). The overall mechanical and hydraulic behaviour of the biodegradable irrigation system was found to be promising (Briassoulis et al., 2011). Biodegradable devices for the controlled release of active, environmentally-friendly ingredients in insect control are also used (Isagro, 2011). Biodegradable mulching film is mainly used in France (700 tonnes), Italy (485 tonnes), Germany (300 tonnes), and Belgium, the Netherlands and Luxemburg (2006 data, *LabelAgriWaste*).

Degradable mulching films made of photo and/or thermo-degradable polyethylene (oxo-degradable or fragmentable) have also been recently introduced in agriculture. These degradable products contain special pro-oxidant components (mainly metal salts) that promote the controlled fast degradation of the PE film

Table 2. Chemical composition of most common agricultural plastic products used in Europe.

Plastic product	Composition	Additives
Greenhouse films	LDPE, LLDPE, EVA/EBA, copolymers, P(EVA) (*LabelAgriWaste*, NHRF), Thermal LDPE, films used as PVF, FEP and PTFE are only used in research and demonstration facilities (materials used in Germany), PMMA and PC (materials used in the Netherlands and Belgium) (Briassoulis et al., 1997)	Carbon black, UV stabilizers, pigments, HALS, silica filler (NHRF), anti-dripping additives, IR additives, anti-dust, anti-fog, nickel quenchers, stabilizers for resistance to agrochemicals (Masterpack, 2013 Nitroerg, 2011; Tarapac, 2011)
Low tunnel films	LLDPE, LDPE (*LabelAgriWaste*, NHRF), P(EVA) (NHRF), thermal LDPE, PVC (materials used in Italy)	UV stabilizers, HALS, anti-dropping additives (*LabelAgriWaste*) or anti-dripping additives, IR additives, anti-fog (Kafrit, 2011; Masterpack, 2013; Tarapac,2011.)
Mulching films	LDPE, LLDPE, EVA, copolymers	Coloured pigments, UV stabilizers, carbon black
Direct cover	Spun-bonded non-woven PP fabric (20–50 μm) PP + PA (nonwoven), PE perforated with 500–1000 holes/m^2 (30–50 g/m^2) [Robinson, 1991), LDPE–EVA	UV-stabilized, coloured pigments
Silage films	Most popular structure: inside and outside layers of LLDPE, EVA, poly isobutylene, middle layer of LLDPE and possible recycled trim (Dow Europe, 2004), atactic PP or high-strength PE–metallocenes (materials used in Greece) (Cabot, 2011)	Oxygen permeability, UV stability, tear and puncture resistance (materials used in Nordic countries) (Napco Modern Plastic Products Company, 2013; RKW, 2011), carbon black or black and white colourants, titanium dioxide (Cabot, 2011), cling masterbatches (Dow Europe, 2004)
Bale wrap and shrink wrap films	LLDPE co-extruded, PP, HDPE, PVC	Black and white colourants, UV stabilizers, anti-dripping additives titanium dioxide, carbon black, metallocenes blends and tackifiers (materials used in UK), antistatic additives(O2inWines International Association, 2011)
Irrigation systems	Irrigation pipes: LDPE, HDPE Irrigation tapes: LDPE, premium ester and ether-polyurethane, PE, PVC, PP, vulcanized thermoplastic elastomers (Norres Industrial Hoses, 2011), glass-reinforced plastic, Fibreglass-reinforced polyester resin	Coloured pigments, carbon black
Agrochemicals containers	PET (O2inWines International Association, 2011), LDPE–HDPE, coextruded, PA, PBT, PP, PVOH/the majority is multilayer plastic, EVOH (materials used in Sweden) (Tarapac, 2011)	Coloured pigments, UV stabilizers, additives offering thermal resistance (Tarapac, 2011)
Fertilizer sacks	PE, PP mono- or bi-color 3-layer and UV-stabilized co-extruded film	UV-stabilized, coloured pigments (materials used in France)
Hydroponic sacks	LDPE, LLDPE, co-extruded	White and black pigments, UV stabilizers
Nets	Nets for collecting (olives, nuts): HDPE/PP Woven nets (hail, bird, shade): HDPE, PP, LLDPE	UV-stabilized, pigments (white and black)
Strings, other	Strings: PP	UV stabilizers, colourings
Disinfection films	Regular LLDPE film, special three-layer virtually impermeable film, PA	UV-stabilized (Plastika Kritis, 2011)

LDPE: low-density polyethylene; LLDPE: linear low-density polyethylene; EVA/EVB: ethylene-vinyl acetate/ethylene-vinyl butyrate; p(EVA): poly(ethylene-vinyl acetate); NHRF: National Hellenic Research Foundation; PVF: polyvinyl fluoride; FEP: fluorinated ethylene propylene; PTFE: polytetrafluoroethylene; PMMA: polymethyl methacrylate; PC: polycarbonate; PP: polypropylene; PA: polyamide; PE: polyethylene; HDPE: high-density polyethylene; PVC: polyvinylchloride; PET: polyethylene terephthalate; PBT: polybutylene terephthalate; PVOH: poly(ethenol); EVOH: ethylene vinyl alcohol; UV: ultraviolet; HALS: hindered amine light stabilizers; IR: infrared.

into very small fragments through its exposure to heat or light. Products made from polymers with metal complexes for agricultural applications include fragmentable mulching films, 15–20 μm thick, and tree shelters. Degradation of these polymers is invariably activated by a transition metal. The main difference between plastics containing metal salts and other photodegradable materials is its ability to break down in the absence of solar radiation. Usually, depending on the cultivation, the fragmentable mulching films are applied on fields in mid-February to March and they begin to degrade in June. By the end of August or September they are almost completely degraded/fragmented. The small fragments are incorporated into the soil through rototilling, like the biodegradable mulching films, and the plant remains, but their possible environmental and toxicological effects have not been studied thoroughly (Briassoulis and Dejean, 2010; Kyrikou and Briassoulis 2007). In any case, strong concerns on the possible biodegradation of these materials have been expressed in the literature, and the relevant scientific questions remain open (Biron, 2005; Briassoulis and Dejean, 2010; Garthe and Kowal, 2001). Furthermore, these films do not pass the compostability standard EN 13432 (2005) requirements.

The marketing of the fragmentable mulching films and other photo- and/or thermodegradable PE products is very strong. In France, 2000 tonnes of fragmentable mulching films were used in 2006, and its use is increasing in the market, year by year. In Spain, the main category of degradable agricultural plastics is oxo-degradable mulching film. This film is used mainly in Extremadura, Aragon, Navarra, Murcia and Castilla-La Mancha. Very recently, it was announced that the development of the 'oxo-degradable' mulch in the region of Murcia is Spain covers more than 11,000 ha (the greatest concentration in Europe). Information released in February 2007 by the main producer (CIBA, 2007) suggests the expanding use of this material in Spain and Portugal.

Methodology for the estimation of APW generation

General approach for estimation of agricultural plastics used and waste generated

This section deals with the quantification of the agricultural plastics used and the APW generated in Europe. APW represents a small fraction of the total plastic waste generated in Europe. The market of the agricultural plastics is too fragmented to have a few players from which to collect data. The agricultural services of the agricultural ministries of most European countries do not have statistics or reports on agricultural plastics. Furthermore, published statistics are often contradictory. Despite these difficulties, under the given circumstances, the work carried out resulted in collecting systematically from various independent sources, reports, statistics, literature, data from the relevant industry and industrial associations, and data through direct contacts and interviews. The quantitative data from different sources were also compared to each other in order to identify possible controversies and justify their reliability. More specifically, the following approach was employed.

Primary statistical data. Primary data were collected where such data existed and an effort was made to identify and reconcile possible discrepancies. In particular, for France, Finland and Cyprus, direct data were provided for specific categories of plastic products consumed and the plastic wastes generated. Also, direct data for the main categories of agricultural plastics was collected for the UK, the Netherlands and the Scandinavian countries based on information available from the corresponding Ministries of Agriculture, the literature, and the relevant industry and industrial associations. For Spain and Greece, direct data were available for containers of agrochemicals, and for Greece and Italy for silage films. These data were also compared with data from the marketing departments of some big plastic producers. If primary data were not available, estimation was made based on the cultivation areas (as described below).

Estimated statistical data. The estimations of APW were based on cultivation areas. Appropriate factors were developed and used to convert the cultivation areas into estimated quantities of APP used and then into APW generated. Thus, statistics for the protected horticultural cultivation areas were used to estimate the corresponding quantities of agricultural films used. Irrigated areas were used to estimate the quantities of irrigation pipes, while arable areas and areas of vineyards, orchards, etc., were used for the estimation of other categories of agricultural plastics. The nature of agricultural films used (e.g. thickness) and the duration of their use (e.g. how many consecutive cultivation periods before their replacement) vary from country to country. As these parameters affect the conversion factor from cultivated areas into APW, it was considered necessary to analyse the relevant practices in the particular countries. The accuracy of these estimations depends strongly on the accuracy of the available statistics of the cultivated areas, the dynamics of the cultivations and the reliability of the data provided for the APP characteristics and their useful lifetime used for the calculation of the conversion factors. The dynamics of the cultivations resulting in changes from one year to the next and the variability of the materials used (e.g. introduction of new APP in the market) add to the uncertainty. Accordingly, these estimations should be used with caution and only as indicative of the real figures. The methodology proposed, however, is generally applicable and may provide the best available estimate for regions for which no primary APW statistical data are currently available.

Conversion factors for estimating agricultural plastics used and waste generated

Special conversion factors estimated for different countries. Table 3 summarizes the conversion factors derived and used in order to transform areas (ha) of cultivated land in Spain, Greece and Italy to tonnes of plastic used, as well as the lifetime considered for each agricultural plastic product in order to transform the used plastic to waste generated. These factors were applied to only those cases for which no reported data were available for the regions considered and/or specific agricultural plastic products. The following text provides the calculations and the assumptions used to derive these factors.

Greenhouse films. The assumption made for the greenhouse films in Greece is that a typical area of 1000 m^2 of cultivation under greenhouse film corresponds to a film surface of 1420 m^2 (area of 20 m × 50 m with an average height of 3 m in Greece; surface factor 1.42). For an average thickness of the greenhouse film of 200 μm and assuming the density of the LDPE film to be 0.935 kg/l (0.917 is typical of LLDPE without any additive; the film density is usually higher depending on the composition of the film, i.e. layers of different composition and additives; the higher the density the higher the conversion factor in a proportional way) the average conversion factor for the greenhouse film quantity is estimated to be 2655 kg/ha. These data were

Table 3. Conversion factors to transform hectares (ha) of cultivated land to kg of plastic used and then to waste generated in Spain, Greece and Italy.

Application	Spain		Greece		Italy	
	Quantity of plastic used (kg/ha)	Quantity of plastic waste (kg/ha/yr)	Quantity of plastic used (kg/ha)	Quantity of plastic waste generated (kg/ha/yr)	Quantity of plastic used (kg/ha)	Quantity of plastic waste generated (kg/ha/yr)
Mulching	322	322	318[b] 152[c]	106 152	335	335[p]
Low tunnel	450–470	450–470	280.5[d]	280.5	795[j]	795
Greenhouse/ high tunnel	1850–2200/1665–1950[a]	463–550/832.5–975.0	2655/1310[e]	664/655	2400/1515–2398	800/1515–959[q]
Silage	1015	1015	No conversion factor used[f]		No conversion factor used[k]	
Agrochemical containers	N/A	N/A	N/A	N/A	0.5/3.0/1.0[l]	0.5/3.0/1.0
Fertilizer sacks	N/A	N/A	3.00/4.50/2.25/1.50[g]	3.00/4.50/2.2/1.50	3/2[m]	3/2
Nets	N/A	N/A	500h	100	500[n]	100
Irrigation thin wall pipes and rigid pipes	N/A	N/A	219/175/127[i]	27.5/22.0/16.0	140[o]	140

N/A: not available
[a]Greenhouse average lifetime considered: 4 years/high tunnels average lifetime considered 2 years.
[b]Quantities referred to mulching film area for asparagus cultivation (film renewed every 3 years).
[c]Quantities referred to mulching film area for watermelon, melon and strawberries cultivations (films renewed every year).
[d]Quantities referred to low tunnel area (films renewed every year).
[e]Quantities referred to greenhouse area (films renewed every 4 years)/walk-in tunnels films renewed every 2 years.
[f]Total agricultural plastic waste of silage film quantity available—renewed every year—500 t/yr.
[g]Quantities referred to arable land, horticultural cultivations, vines, orchards respectively (application per year).
[h]Quantities referred to vineyards (anti-hail) and olive trees (collection nets) (average lifetime assumed: 5 years).
[i]Quantities of rigid pipes referred to horticultural/vineyard/rest of irrigated areas (average lifetime assumed: 8 years).
[j]Quantities referred to low–medium tunnel area (films renewed every year).
[K]Total agricultural plastic waste of silage film quantity available 8500 t/yr.
[l]For arable land/for orchards/for vegetables (average national – application per year).
[m]Polyethylene (PE) sacks (50 kg) for arable land and vegetables/PE sacks (50 kg) for orchards (average lifetime considered/application per year).
[n]Agricultural plastic waste for nets used with vineyards (assuming that the same applies to other types of nets) (average lifetime assumed: 5 years).
[o]Thin wall pipes or tapes used with mulching film (one-season use).
[p]Average lifetime considered: 1 year.
[q]Greenhouse average lifetime considered: 3 years/high tunnels average lifetime considered 1–2, 5 years.

confirmed by the representatives of two companies: Agrek C. Samantouros S.A. (retailer; http:www.agrek.gr) (3000 kg/ha) and Plastika Kritis S.A. (producer) (2500 kg/ha). As the average lifetime of the greenhouse films in Greece is 4 years, the corresponding conversion factor for the plastic waste generated from greenhouse films becomes 664 kg/ha/yr. In the case of walk-in tunnels in Greece, usually films 80–120 μm are used for a period of 2 years (e.g. for strawberry cultivation). Then, a typical area of 1000 m^2 of cultivation under high-tunnel film corresponds to a film surface of 1400 m^2 (surface factor: 1.4). For an average thickness of the high-tunnel film of 100 μm and assuming the density of the LDPE film to be 0.935 kg/l the average conversion factor for the high-tunnel film quantity is estimated to be 1310 kg/ha. As the average lifetime of the high-tunnel films in Greece is 2 years, the corresponding conversion factor for the plastic waste generated from greenhouse films becomes 655 kg/ha/yr.

In the case of Italy, the following data were used for the calculation of the corresponding conversion factor regarding greenhouse films: average film thickness of 180 μm; surface factor (film surface/land surface) of 1.333; average film density of 1.0 kg/l; average life time of 3 years. Accordingly, the conversion factor for the greenhouse films in Italy is calculated to be 2400 kg/ha. The corresponding APW generated is 800 kg/ha/yr.

Walk-in tunnels (high tunnels) are also employed in Italy with the following characteristics: one category of these films has a thickness range of 130–150 μm and working life 12 months, and another category has a thickness range of 180–200 μm for a working life 2–3 years. The density of these films is 0.935 kg/l and the surface factor is 1.3–1.4. Then, the plastic used per ha of land is 1514.7 kg/ha and 2398.3 kg/ha correspondingly for the two groups of films, and the plastic waste generated is also 1514.7 kg/ha/yr and 959.31 kg/ha/yr.

In Spain, the majority of greenhouse films is made of LDPE containing three coextruded layers and has an average thickness of 200 μm. The quantity used per ha of cultivated land is 1850–2200 kg/ha. The average lifetime of these films in the field is 48 months. Therefore, the quantity of greenhouse waste generated per year is 463–550 kg/ha/yr. In the case of walk-in tunnels in Spain, their average thickness is 180 μm (normal and thermal LLDPE), and their average lifetime is 2 years. Therefore, the quantity used per ha is 1665–1950 kg/ha and the waste generated per year is 832.5–975.0 kg/ha/yr.

Low-tunnel films. The assumption made for Greece was that 0.1 ha of cultivation under low-tunnel film corresponds to a surface of 50 m × 20 m = 1000m^2 that is covered by LLDPE/LDPE film of 30 μm (range 17–80 μm) with a density of 0.935 kg/l (the density may vary depending on the composition of the film and the additives used). Assuming that the empty spacing between the rows of the low tunnels is counterbalanced by the developed curved surface area of the film, the average conversion factor for the low-tunnel film quantity is estimated to be 280.5 kg/ha. As this category of plastic film is replaced each season, the plastic waste generated from low tunnel films remains 280.5 kg/ha/yr.

The corresponding parameters considered for the case of low-to-medium-tunnel films in Italy are the following: thermal films with thicknesses ranging from 70 to 100 μm and a density of 0.935 kg/l. Also, the surface factor (film surface/land surface) is 1, and the lifetime of these films is limited to 1 year. Then, the conversion factor for this agricultural product in Italy is estimated to be (thickness 85 μm) 795 kg/ha. The corresponding APW generated is 795 kg/ha/yr. Based on the above values, it is interesting to note that the apparent 'discrepancy' of the conversion factors for low tunnels used in Greece and Italy is basically attributed to the different thickness of the plastic low-tunnel films used in these countries (in Italy the average thickness seems to be almost three times greater than in Greece).

In Spain, low-tunnel films are composed of LDPE with a film thickness 40–50 μm and EVA with a film thickness of 50–75 μm. Also, considering the height of low tunnels to be 0.5 m, the quantity used per ha of cultivated land is 450–470 kg/ha. The average lifetime of these plastics is one cultivation season (2 months), so the waste generated per year is 450–470 kg/ha/yr.

Mulching films. The assumption made for Greece was that 0.1 ha of a typical cultivation with mulching film corresponds to a surface of 50 m × 20 m = 1000 m^2 that is covered at a percentage of 65% by LLDPE/LDPE film of an average thickness of 25 μm (e.g. melon, watermelon, courgette) or 50 μm (asparagus) with a density of 0.935 kg/l (the density may vary depending on the composition of the film and the additives used). Taking into account the various sizes of the film width and the empty spacing between the rows of the mulching films, partially counterbalanced by the buried film area for fixing the film along the two sides, the average conversion factor for the mulching film quantity is estimated to be in the range of 152 kg/ha (e.g. melon, watermelon, horticultural products) to 318 kg/ha (asparagus). The mulching film (with the exception of the asparagus cultivations) is replaced each season. Consequently, the plastic waste generated is 152 kg/ha/yr. In the case of asparagus, the mulching film is replaced every 3 years and the corresponding plastic waste is 106 kg/ha/yr. Furthermore, for the calculation of the mulching films used per county in Greece, the rough assumption is made that mulching films are used, on average, for 60% of the horticultural cultivations and 100% of the asparagus cultivations.

The data used in Italy for mulching films are different. The majority of the films have thicknesses in the range of 40–50 μm (average: 45 μm), with an average density of 0.93 kg/l. The surface factor is in the order of 80%. Subsequently, the conversion factor for the mulching films in Italy is calculated to be 335 kg/ha. The corresponding APW generated is 335 kg/ha/yr.

In Spain, mulching films are composed of LLDPE with a film thickness of 15 μm and LDPE with a film thickness of 20–25 μm. Considering that mulching films cover 60% of the field area, the plastic used per ha of land is 322 kg/ha. Also, the average lifetime of the mulching films in Spain is 4 months (one cultivation season), so the mulching film waste generated is 322 kg/ha/yr.

Irrigation pipes. In Greece, the great range of the various thick and thin wall pipes combined with lack of data for their use led to a rather rough estimation of the annual use and waste produced from irrigation pipes. Thin wall pipes and tapes are not widely used in Greece. It was assumed that rigid pipes are used for orchards, horticultural cultivations, arable crops and vines. The average weight of rigid irrigation pipes varies from 0.044 kg/m (16-mm diameter pipes), 0.063 kg/m (20-mm diameter pipes) to 0.10 kg/m (32-mm diameter pipes) or higher. Assuming that all horticultural cultivations in Greece (111,140 ha; Eurostat, 2007) use rigid wall drip irrigation pipes (average *Φ16*, 0.95 mm thick) at an average distance of 2 m, a conversion factor of 219 kg/ha is estimated for the irrigation pipes used for these cultivations. The total irrigable area for Greece of 1,555,310 ha (Eurostat, 2007), from which 126,100 ha is vineyards, 111,141 ha horticultural cultivations and 1,318,069 ha rest of irrigated area (e.g. arable land, olive groves, etc.). Assuming an average spacing of the irrigation pipes of 2.0 m for horticultural areas the quantity of the used rigid irrigation pipes (average *Φ16*, 0.46-mm-thick pipes) is estimated at 219 kg/ha. Assuming an average spacing of the irrigation pipes of 2.5 m for vineyards the quantity of the used rigid irrigation pipes (average *Φ16*, 0.95-mm-thick pipes) is estimated at 175 kg/ha. Assuming an average spacing of the irrigation pipes of 5 m, the quantity of the used rigid irrigation pipes (average *Φ20*, 1.6-mm-thick pipes) is estimated at 127 kg/ha for arable land and rest of irrigated area. To convert the above data to APW, the average lifespan of the rigid pipes was assumed to be 8 years (6–10 years). The corresponding irrigation rigid pipes waste is estimated at 27.5 kg/ha/yr for horticultural cultivations, 22 kg/ha/yr for vineyards and 16 kg/ha/yr for rest of irrigated area.

In Italy, one way to evaluate the waste generated is to consider the length of mulching film and assume that under it, irrigation thin film tapes are installed. A quantity of 335 kg of mulching film corresponds to an area of 8005 m^2. Considering an average film width of 1.2 m it comes out at a running length of 6670 m. Thin wall irrigation pipes/tapes (16 mm pipes; 0.46 mm thick) is estimated at 0.021 kg/m. Thus, 6670 m of thin wall pipe × 0.021 kg/m. As they are replaced yearly they result in 140 kg/ha/yr of waste.

Nets. The porosity and weight of the nets in Greece varies with the application (e.g. anti-hail nets mainly for vineyards and some orchards; collection nets for olive trees areas, etc.). According to Arrigoni SpA (2009) the nets used in vineyard crops or olive trees have an average weight of 50 g/m^2. A conservative average life span of 5 years was assumed for nets in Greece (good quality nets may last 7–10 years). As a result, the APW conversion factor for nets comes out to 100 kg/ha/yr.

For Italy, according to Arrigoni SpA (2009) the quantity of the nets used for vineyards and the anti-hail nets is estimated at 500 kg/ha. Assuming a life span of 5 years, the APW generated is 100 kg/ha/yr.

Fertilizer sacks. The average use of fertilizers in Greece (sacks/ha/yr) was estimated separately for crops on arable land (20), horticultural cultivations (30), vines (15) and orchards (10). Assuming that the average fertilizer bag weighs 150 g (Thrace Plastics, 2011), and that the fertilizer consumption practices in Greece are 20 bags/ha for crops on arable land, 30 bags/ha for horticulture cultivations, 15 bags/ha for vineyards and 10 bags/ha for trees, the amounts of APW generated by the bags of fertilizers is estimated at 3 kg/ha/yr for arable land, 4.5 kg/ha/yr for horticultural cultivations, 2.25 kg/ha/yr for vineyards and 1.5 kg/ha/yr for orchards.

The conversion factors used for Italy are analytically shown in Table 3 (UNIBAS, 2010).

Silage films. In Spain, the quantity of silage film used per ha of land is 1015 kg/ha and considering that its average lifetime is 1 year, then the silage film waste generated is 1015 kg/ha/yr.

Agrochemical containers. For Italy, the conversion factors have been estimated at 0.5, 3.0 and 1.0 kg/ha/yr of agrochemicals plastic packaging waste generated per area of land for arable land, for orchards and for vegetables respectively (average national estimations).

Common conversion factors used when no data for agricultural plastics were available. For those specific plastic product categories for which no primary data were available in France, Germany, Finland, Cyprus, UK, the Netherlands and the Scandinavian countries, as well as for the countries where no data at all were available (Austria, Czech Republic and Slovakia, Hungary, Malta, Poland, Portugal, Belgium and Luxemburg, Sweden, Albania, Bulgaria, Croatia, Romania, Russia, Serbia and Switzerland), the analysis was based on the following methodology.

Estimated areas of protected cultivations were based on a report by Congresso Internacional de Plasticos para la Agricultura (CIPA) [survey published in 2006 presenting 2004 data; including areas of protected cultivations using plastic films (ha), and areas of cultivations using hydroponics and irrigation systems (ha), as well as to the used quantities of silage films and PP strings within Europe]. The areas of protected cultivations reported by CIPA were 'translated' into tonnes of agricultural plastic film used per year by applying the conversion factors reported in Table 4. The factors in Table 4 are based on the technical experience of PATI S.p.A. (an agricultural film producer, selling films throughout Europe). The assumptions on which these factors were calculated are presented in Table 4 and concern the average thicknesses for greenhouse, low tunnel, mulching and direct cover films of the vast majority of the corresponding agricultural applications in Europe. The application of these factors to translate cultivation areas to used agricultural plastics, and then by taking into account the lifetime of these films into tonnes/year of waste generated (APW), yields only a rough estimation as the thickness of the films and their useful life may differ from one country to the next.

Comparing the data derived from CIPA calculations against primary data (where available) or against data estimated based on verified information on the cultivated areas, etc. discrepancies were identified that in some cases were significant (partially attributed to the dynamics of the cultivations). It was concluded that some of the data reported by CIPA might be questionable today.

Table 4. Conversion of areas of protected cultivation to the corresponding plastic used and the plastic waste generated (PATI SpA, 2010).

Agricultural film category	Conversion of area of land to kg of plastic used (kg/ha)	Quantities (kg) of plastic used and plastic waste generated
Greenhouse[a]	1580	It is assumed that the amount of agricultural plastic films used divided by the years of the life-time of the corresponding films yields the amount of the (clean, without foreign materials) agricultural plastic waste generated (APW t/ha/yr)[e]
Low tunnel[b]	1115	
Direct cover[c]	400	
Mulching[d]	306	

[a]Thickness of greenhouse films:
- films of annual stabilization (65% of market) = 150μm.
- films of long life stabilization (35% of market) = 200 μm.

So, the average is 168 μm and the consumption is therefore 10,000 × 0.168 × 0.94 = 1580 kg/ha.
Tunnel-shape factor multiplied for ratio of cropped surface is close to 1.
[b]Thickness of low tunnel films:
Range of film thickness: 80–100 μm, so the average is considered to be 90 μm.
The consumption is therefore 10,000 × 0.09 × 0.94 = 846 kg/ha.
Low tunnel shape factor = 1.55 and the ratio of cropped surface = 0.85.
The consumption is therefore 846 × 1.55 × 0.85 = 1115 kg/ha.
[c]Thickness of direct cover films:
In this case, the concept of thickness is superseded by the weight in g/m^2 which can be assumed in 40 g/m^2 or 400 kg/ha.
PATI is not producing such items, as it is a 'woven-not woven' polypropylene material.
[d]Thickness of mulching films:
Average film thickness = 50 μm.
The consumption is therefore: 10,000 × 0.05 × 0.94 = 470 kg/ha.
Ratio of mulched surface = 65%; therefore, 470 × 0.65 = 306 kg/ha.
[e]This assumption is based on the fact that the trend for the agricultural plastic films in Europe was found, on the average, to be almost constant over the last years (Espi et al., 2006).

Table 5. Main cultivations using agricultural plastic films in Europe[a].

Greenhouse films	Low tunnel films	Mulching films	Direct cover films
Melon, watermelon, strawberry, tomatoes, cucumbers, lettuce, eggplants, peppers flowers, ornamental plants nursery (Jensen and Malter, 1995; PATI, 2010; Plastika Kritis, 2011)	Strawberry, melon watermelon vegetables, carrot, cotton (Marten 1992–1993, PATI, 2010; Plastika Kritis, 2011)	Tomatoes, lettuce, marrow, onion, eggplants, beans strawberry, watermelon, melon, asparagus cotton (Daios Plastics; PATI, 2010; Two Wests and Elliott, 2011)	Leaf and root vegetable crops vineyard, tobacco, tomatoes, potatoes, melon, water melon, strawberry (Daios Plastics; Gimenez et al., 2002; Jensen and Malter, 1995; Marten 1992–1993)

[a]The list is not exclusive; the most typical applications are shown.

APW generation analysis in Europe

Temporal distribution of APW

Table 5 shows the main cultivations using agricultural plastic films in Europe (only the most typical applications are shown). The prevailing cultivations using agricultural plastic films include all kinds of horticultural crops: fruits, vegetables and herbs and flowers. Mulching films are also used in some cases of cotton cultivations in Spain and Greece, and recently in vineyards.

Table 6 shows the periodicity of waste generation for agricultural films from protected cultivations (lifetime and time of the year the films are removed from the field, means of removal of the films, and main contaminants from use and removal of the films). Table 6 also shows that the different waste streams are removed at different periods of the year which means that the consolidation of a waste stream and prevention from mixing the streams is rather easy, provided the farmers transport the removed plastic soon after removal from their field to the consolidation station (Briassoulis et al. 2008b, 2010). Although means of mechanized removal of the plastic films exist, the removal procedure is mainly performed manually in many countries. The impurity levels of the low tunnel and mainly of mulching films (that come in contact with the soil) can be excessive compared to that of the greenhouse films.

Table 7 shows the periodicity of waste generation and means of removal from the field for some other agricultural plastic steams (other than protected cultivation films). As in the case of the previous streams the majority of these streams can be easily consolidated (at least for a specific geographic location) as the operation that generates the stream takes place at a specific time of the year across this location. For example, most of the fields are fertilized at the same periods of the year. Therefore, the empty fertilizer sacks can be collected all at the same time from the particular location.

Table 6. Periodicity of waste generation and means of removal of the agricultural plastic films from protected cultivations and main contaminants from use and removal.

Film category	**Life time**	**Removal period**	**Removal methods**	**Contamination of waste from field/use** (% of total mass) (LabelAgriWaste project)
Greenhouse film	1–3 yrs[a32] 3–5 yrs[b33] 3–4 yrs[c34] 2–5 yrs[d35]	Different periods per country (e.g.): • during summer and before autumn • August–October[e] • September–November[f] • October–November[g]	Manually and mechanically	• 15–20%: impurities, mainly agrochemicals • Total dirt (e.g. water, soil, organic waste; shading material): 20
Low tunnel film	One season	Depending on cultivation	Manually and mechanically	• Total dirt: 60–65 • Total dirt: 30 • Total dirt: 50 • Total dirt: 35–50; water 9–20
Mulching film	One season (exception: asparagus three seasons)	End of the crop (usually during summer and September)	Manually and mechanically	• Total dirt: 60–80 • Total dirt: 70 • Water: 1–14; dirt, including organic pollution and soil: 3–53
Direct cover film	One season	Depending on cultivation	Manually and mechanically	Dust, soil, organic material (leaves, insects), agrochemicals • Total dirt: 10

[a]Spain.
[b]Italy.
[c]France.
[d]Greece.
[e]South Greece.
[f]Central Greece.
[g]North Greece.

Table 7. Periodicity of waste generation and means of removal of some agricultural plastics (other than protected cultivation films) and main contaminants from use and removal.

Film category	Lifetime (years)	Removal period	Removal methods	Contamination of waste from field/use
Irrigation tubes/drippers	10–20	According to cultivation	Manually and mechanically	Humidity, dirt, organic pollution (leaves, insects), soil, adhesives, glues, mixed plastics, agrochemicals
Nets	6–10	For vineyard cultivation: removed in August–September,[a] January–February or up to spring[b] For olive collection: removed after collecting the crop (usually December–January)	Manual	Dust, organic material (leaves, insect), agrochemicals
Fertilizer sacks	Single use	Variable	Manual	Soil, fertilizers, agrochemicals
Bale wrap	Single use	Variable	Mechanically or manual	Humidity, organic pollution (e.g. residues of herbaceous plants, hay) and adhesives
Silage films	Single use	Variable	Manually and mechanically	Organic material (e.g. residues of herbaceous plants, straw, hay)
Strings	Single use	Variable	Manual	
Agrochemical containers	Single use	Variable	Manual	Agrochemicals

[a]Greece.
[b]Italy.

Spatial distribution of APW

Spatial quantitative distribution of APW at European level. The mapping of the APP and APW in Europe per country carried out in the framework of the *LabelAgriWaste* programme was based on systematically collecting all currently existing information in most European countries concerning agricultural plastics use and APW generation (when such data were available) and verifying them by comparing the data obtained from various sources and cross-checking them, or estimating the corresponding quantities according to the methodology already analysed in the 'Methodology for the estimation of APW generation' section. Tables 8 and 9 present the estimated annual agricultural plastic film use and waste generated in European countries for protected cultivations for the period 2003 to 2010.

The data for the waste generation from silage film, bale wrap and polypropylene twine are also summarized in Table 10 in terms of the amount of APW (t/yr). Some of these data were generated and/or verified by the *LabelAgriWaste* project.

The data for the waste generation from irrigation systems, fertilizer sacks, agrochemical containers and nets around Europe are also summarized in Table 11. All these data were generated by the *LabelAgriWaste* project.

Conclusions

The current research on the mapping and analysis of the APW generation and consolidation in Europe was conducted in the framework of the European project 'LabelAgriWaste'. In particular, the special characteristics and the critical parameters of the agricultural plastic wastes generation in Europe were analysed.

Despite the fact that officially reported information on the agricultural plastic use in most of the European countries is sporadic or even unreliable or unavailable, data from official European Services such as the Ministries of Agriculture and Statistical Organizations were combined with information from regional services, local agronomists, retailers and farmers, site visits and interviews with the sales departments of major producers, importers and converters of agricultural plastics. In the case of lack of any data, the agricultural plastic products used were estimated indirectly based on the recorded cultivated areas. To this end a methodology was developed and presented.

The generation (use, quality) of agricultural plastic waste in Europe was quantified and analysed by region and category. The periodicity of the waste generation mechanism was also quantified and analysed. The potential of possible replacement of conventional plastic materials by alternative materials (e.g. bio-based biodegradable in soil plastic films) was briefly documented.

Quantitative data and analysis of the agricultural plastic waste generation by category, geographical distribution, compositional range and physical characteristics of the agricultural plastic waste per use and the temporal distribution of the waste generation in Europe are presented. The chemical composition range and the additives used during the production phase are also defined.

Table 8. Estimated annual protected cultivation plastic film in use and waste generated in Spain, Italy, Greece and France for the period 2003–2011[a].

Country	**Greenhouse and walking tunnel films** (t/yr)		**Small tunnel films** (t/yr)		**Direct covers NW fabrics** (t/yr)		**Mulching films** (t/yr)		**Sum of specific agricultural plastic use and waste generation per country** (t/yr)	
	In use	Waste	In use	Waste	In use	Waste	In use	Waste	In use	Waste
Spain (2010)	113,391.3	32,144.2	1242.0	1242.0	**1540.0**	**1540.0**	15,101.8	15101.8	**13,1275.1**	**50,028**
Italy (2005)	54,675.0 (greenhouse films)	18,225.0 (greenhouse films)	29,350.0	29,350.0	25,000.0[d]	3571	46,495.0	46,495.0	**155,520.0**	**97,641.0**
Greece	15,263.8 (2006–2007)	4588.6 (2006–2007)	2393.6 (2003)	2393.6 *(2003)*		**440.0**	12,512.6[e] (2007)	11,556.2 (2007)	**30,170.0**	**18,978.4**
France	9600.0 (2007)	5400 (2011[b])	7972 (2011[c])	7972 (2011)			5500 (2011[f])	17,000 (2011)	**23,072.0**	**30,372.0**
Total	192,930.1	60,357.8	40,957.6	40,957.6	26,540.0	5551.0	79,609.4	90,153	**340,037.1**	**197,019.4**

[a]All data in bold are for 2004 and they are based on the data of Congresso Internacional de Plasticos para la Agricultura (CIPA), while the non-bolded data were generated by the LabelAgriWaste project.
[b]Source: CPA (Comite Francais des Plastiques en Agriculture; http://www.plastiques-agriculture.fr/). Assuming that the quantities of the consumed greenhouse and high tunnels coincide with the quantities of the wasted films. 2007 data (source: *LabelAgriWaste*): 2742.8t/yr.
[c]Source: CTIFL (Centre Technique Interprofessionnel des Fruits et Légumes), 2011, http://www.ctifl.fr/. Number referring to low tunnel and solarization films. 2007 data (source: *LabelAgriWaste*): low tunnel film waste 7050t/yr
[d]Only vineyard-covering film.
[e]Assuming that the mulching films are used on the average for 60% of the horticultural cultivations and 100% of asparagus cultivations.
[f]Source: CTIFL (Centre Technique Interprofessionnel des Fruits et Légumes), 2011, http://www.ctifl.fr/. The quantity of mulching film waste 17,000 t/yr for 2011 contains contamination. 2007 data (source: *LabelAgriWaste*): mulching film waste 19,600 t/yr.

Table 9. Estimated annual protected cultivation plastic film waste generated in other European countries for the period 2004–2007[a].

Country	**Greenhouse and walking tunnel films** (t/yr)	**Small tunnel films** (t/yr)	**Direct covers NW fabrics** (t/yr)	**Mulching films** (t/yr)	**Sum of specific agricultural plastic consumption & waste generation per country** (t/yr)
Austria	**711.5**				**711.5**
Czech Republic and Slovakia	**7746.9**			**604.6**	**8351.5**
Denmark	**31.6**				**31.6**
Finland (2005)	316.0				**316.0**
Hungary	**10,276.5**	**2766.8**	**4400.0**	**725.5**	**18,168.8**
UK	250.0 (2004)	250.0 (2004)	13,200.0	23,624 (2005)	**37,324.0**
Germany	**1106.7**	**1106.7**	**12,320.0**	**4534.5**	**19,067.9**
the Netherlands (2006)	**632.4**		**1430.0**	3000–4000.0	**5062.4–6062.4**
Malta	**158.1**				**158.1**
Poland	**3162.0**	**885.4**	**4400.0**		**8447.4**
Portugal	**4268.7**	**498.0**		**6952.9**	**11,719.6**
Belgium and Luxemburg	**553.4**	**221.3**	**3300.0**	**1027.8**	**5102.5**
Sweden	**94.9**				**94.9**
Cyprus (2007)	240.0	230.0		60.0	**530.0**
Albania	**528.1**				**528.1**
Bulgaria		**2766.8**	**550.0**	**3929.9**	**7246.7**
Croatia	**1897.2**				**1897.2**
Norway				**846.4**	**846.4**
Romania	**1422.9**				**1422.9**
Russia	**5138.3**				**5138.3**
Serbia	**7968.2**				**7968.2**
Switzerland	**948.6**		**1100.0**	**846.4**	**2895.0**
Total	**47,452**	**8725**	**40,700**	**46,152–47,152**	**143,029–144,029**

[a]All bold data are for 2004 and they are based on the data of Congresso Internacional de Plasticos para la Agricultura (CIPA), while the non-bold data are generated by the project LabelAgriWaste.

Table 10. Estimated annual plastic yearly waste generated from silage film, bale wrap and polypropylene (PP) twine in European countries for the period of 2003 to 2007[a].

Country	**Silage film** (t/yr)	**Bale wrap** (t/yr)	**PP strings** (t/yr)	**Sum of specific APW generation per country** (t/yr)
Austria	**3500.0**			**3500.0**
Baltic countries	**3000.0**			**3000.0**
Spain (2004)	16,576.0		7500.0	**24,076.0**
Italy (2005)	8500.0[b]		8000.0	**16,500.0**
France	25,000.0 (2007)	10,625.0 (2007)	18,000.0 (2006)	**53,625.0**
Czech Republic and Slovakia	**2500.0**			**2500.0**
Denmark	**10,000.0**		**2800.0**	**12,800.0**
Finland (2006)	2000.0	5000.0		**7000.0**
Hungary	**4000.0**		**3000.0**	**7000.0**
Greece (2003)	500.0[c]			**500.0**
UK	54,416.0 (2005)	11,500.0 (2004)	5000.0	**70,916.0**
Germany	**29,000.0**		**10,000.0**	**39,000.0**
Ireland	**15,000.0**			**15,000.0**
the Netherlands (2006)	8000.0			**8000.0**
Poland	**3000.0**			**3000.0**
Portugal	**300.0**			**300.0**
Belgium andLuxemburg	**10,250.0**			**10,250.0**

Table 10. (Continued)

Country	Silage film (t/yr)	Bale wrap (t/yr)	PP strings (t/yr)	Sum of specific APW generation per country (t/yr)
Cyprus (2007)		160.0		**160.0**
Bulgaria	**5000.0**			**5000.0**
Switzerland	**3000.0**			**3000.0**
Sweden	**11,000.0**			**11,000.0**
Norway	**7000.0**			**7000.0**
Total	**221,542.0**	**27,285.0**	**54,300.0**	**303,127.0**

APW: agricultural plastic waste.
[a]All data in bold are for 2003 to 2005, and they are based on the data of Congresso Internacional de Plasticos para la Agricultura (CIPA), while the non-bold data were generated by the project LabelAgriWaste.
[b]For several applications: fodder silage, polyethylene (PE) sheets, PE bags, stretch film.
[c]Data from Plastika Kritis (2003). Useful lifetime of silage films in Greece: 1 year.

Table 11. Estimated annual plastic waste generated for micro-irrigation systems, fertilizer sacks, agrochemical containers and agricultural nets in European countries for the period 2003–2006 (LabelAgriWaste data).

Country	Irrigation systems (t/yr)	Fertilizer sacks (t/yr)	Agrochemical containers (t/yr)	Nets (t/yr)	Sum of specific APW generation per country (t/yr)
Spain	75,776.0 (2005)		4000.0[a]		**79,776**
Italy	17,000.0 (2005)	12,700.0 (2011)	2700.0 (2011)	1000.0 (2005)[d]	**33,400**
France		17,000.0 (2006)	8000.0[b]		**25,000**
Finland			1000.0 (2006)		**1000**
Greece	39,265.5 *(2007)*	7373.53 *(2007)*	1103.8 (2004)[c]	9988.9 (vineyard nets, 2002 data)	**57,730.83**
UK		8079.0 *(2005)*	1599.0 (2005)		**9678**
Cyprus	10.0 (2007)				**10**
Total	**132,051.5**	**45,152.53**	**18,402.8**	**10,988**	**206,594.8**

[a]Source: Sigfito (http://sigfito.es/).
[b]Source: Adivalor (http://www.adivalor.fr/en/).
[c]Data from the Hellenic Crop Protection Association, 2004, http://www.esyf.gr/. This quantity includes all plastic containers used for agrochemicals in Greece not only for protected cultivations but also for large arable cultivations areas, vines (grapes and resins), trees (in compact plantations) and open horticultural cultivations. Also, 2012 data provided by local agronomists of National Agricultural Research Foundation (NAGREF) (http://www.nagref.gr) (Chania, Crete) for Crete report 128 t of agrochemical container waste per year.
[d]Scarascia-Mugnozza et al. (2005).

This work represents the first systematic effort to map and analyse agricultural plastic waste generation and consolidation in Europe. Further work at the level of the official European state organizations is needed to refine and enrich this work. The structured information and independently verified data provided through this work were used in the design of an optimized integrated waste management system for the APW chain in Europe (Briassoulis et al., 2010; LabelAgriWaste, 2006–2009).

Acknowledgements

Special thanks are due to Ms. D.Marda from the national Federation of Farmers Associations (PASEGES; www.paseges.gr) for contributing significantly in the effort of collecting information from the farmers by mapping the areas of central and northern Greece. Thanks are also due to the other partners of Labelagriwaste contributed with data from their countries.

Declaration of conflicting interests

The authors do not have any potential conflicts of interest to declare.

Funding

The present work has been supported by the FP6 European project 'Labelling agricultural plastic waste for valorising the waste stream', Collective research, *LabelAgriWaste*, Contract no. 516256-2.

References

Andreasen J and Fitz N (2006) *Open Burning of Agricultural Plastics*. Austin, TX: The Pesticide Stewardship Alliance (TPSA).

APE Europe (Agriculture Plastic Environment) (2012) Press release. Available at: http://www.plastiques-agriculture.com/PDF_telechargeables/DP_APE_Europe_english.pdf (accessed 19 April 2013).

Arrigoni SpA (2009) Technical Protection Textiles. Available at: http://www.arrigoni.it/ (accessed 19 April 2013).

Biron M (2005) Collateral effects of additives Part 2 – Unexpected and surprising effects of specific additives. SpecialChem Company. Available at:

http://www.specialchem4polymers.com/resources/articles/article.aspx?id=2118&q=Collateral%20effects%20of%20additives#Some (accessed 19 April 2013).

Briassoulis D (2004) An overview on the mechanical behaviour of biodegradable agricultural films. *Journal of Polymers and the Environment* 12: 65–81.

Briassoulis D (2007) Analysis of the mechanical and degradation performance of optimised agricultural biodegradable films. *Polymer Degradation and Stability* 92: 1115–1132.

Briassoulis D and Dejean C (2010) Critical review of norms and standards for biodegradable agricultural plastics part I. Biodegradation in soil. *Journal of Polymers and the Environment* 18: 384–400.

Briassoulis D, Waaijenberg D, Gratraud J and Von Elsner B (1997) Mechanical properties of covering materials for greenhouses. Part 1: General Overview. *Journal of Agricultural Engineering Research* 67: 81–96.

Briassoulis D, Aristopoulou A, Bonora M and Verlodt I (2004) Degradation characterization of agricultural low density polyethylene films.*Journal of Biosystems Engineering* 88: 131–143.

Briassoulis D, Babou E and Hiskakis M (2008a) Correlation of key agricultural plastic waste parameters with the quality of the resulting waste stream. *Acta Horticulturae (ISHS)* 801:333–340.

Briassoulis D, Liantzas K and Hiskakis M (2008b) Management of agricultural plastic waste (APW)–a pilot test in Greece. In: *Proceedings of EurAgEng 2008*, Hersonissos, Crete, 23–26 June 2008, OP-325 (1179157), EurAgEng, Bedfordshire, England.

Briassoulis D, Hiskakis M, Scarascia G, Picuno P, Delgado C and Dejean C (2010) Labeling scheme for agricultural plastic wastes in Europe. *Quality Assurance and Safety of Crops & Foods* 2: 93–104.

Briassoulis D, Babou E and Hiskakis M (2011) Degradation behaviour and field performance of experimental biodegradable drip irrigation systems. *Journal of Polymers and the Environment* 19: 341–361.

Brown RP (2004) Polymers in agriculture and horticulture. *Rapra Review Reports* 15: 104.

Cabot Corporation (2011) Masterbatch selection guide for agricultural film applications. Available at: http://www.cabot-corp.com/wcm/download/en-us/mb/MB%20Agricultural%20Film%20Engl-090743.pdf (accessed 19 April 2013).

Castellano S, Scarascia Mugnozza G, Russo G, Briassoulis D, Mistriotis A, Hemming S and Waaijenberg D (2008) Plastic nets in agriculture: a general review of types and applications. *Applied Engineering in Agriculture* 24L 799–808.

CIBA Specialty Chemicals, Case Study (2007) Ciba® ENVIROCARE® AG 1000 Degradable Films, http://www.ciba.com/envirocare_case_study.pdf (accessed July 2008).

CIPA (Congresso Internacional de Plasticos para la Agricultura) (2006) 23-25 Octobre 2006, Buenos Aires (Argentina), CAPPA (Comité Argentino de Plásticos para la Producción Agropecuaria).

DAIOS Plastics [Homepage]. Available at: http://www.daiosplastics.gr/site/home.asp, (accessed 19 April 2013)

Dilara PA and Briassoulis D (2000) Degradation and stabilisation of low density polyethylene (LDPE) films used as greenhouse covering materials. *Journal of Agricultural Engineering Research* 76: 309–321.

Dow Europe (2004) A survey of current practices, trends and opportunities – market report on bale silage, Nordic region. Available at: http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0062/0901b803800621b6.pdf?filepath=silage/pdfs/noreg//003–05301.pdf&fromPage=GetDoc (accessed 19 April 2013).

EN 13432: 2000/AC:2005 (2005) European committee for standardization. EN 13432. Packaging—requirements for packaging recoverable through composting and biodegradation-test scheme and evaluation criteria for the final acceptance of packaging, European standard.

Espi E, Salmeron A, Fontecha A, Garcia Y and Real AL (2006) Plastic films for agricultural applications. *Journal of Plastic Film and Sheeting* 22: 85–102.

EUPC (2007) European plastics converters. Plastics for agriculture. Available at: http://www.plasticsconverters.eu/markets/agriculture (accessed 19 April 2013).

European Bioplastics (2001) On the implementation of the Community Strategy for dioxins, furans, and polychlorinated biphenyls. Available at: URL: http://www.european-bioplastics.org/European Commission (accessed 19 April 2013).

Eurostat (2007) [Homepage]. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/ (accessed 19 April 2013).

Garthe JW and Kowal PD (2001) *The Chemical Composition of Degradable Plastics*. C-17, PA: College of Agricultural Sciences Cooperative Extension, Pennsylvania State University

Gimenez C, Otto RF and Castilla N (2002) Productivity of leaf and root vegetable crops under direct cover. Scientia Horti*culturae* 94: 1–11.

Grima S, Bellon-Maurel V, Silvestre F and Feuilloley P (2001) A New Test Method for Determining Biodegradation of Plastic Material Under Controlled Aerobic Conditions in a Soil-Simulation Solid Environment. *Journal of Polymers and the Environment* 9:39–48.

Gross RA and Kalra B (2002) Biodegradable polymers for the environment. Green Chem*istry* 2002; 297: 803–807.

Hemming S, Kempkes F, Van Der Braak N, Dueck T and Marissen N. Filtering natural light at the greenhouse covering—better greenhouse climate and higher production by filtering out NIR? *Acta Horticulturae* 2006; 711: 411–416

Hiskakis M and Briassoulis D (2006) Design of agricultural plastic waste chain for Greece from generation to disposal; a pilot test for energy recovery. In: *Proceedings of the international conference of agricultural engineers, AgEng, world congress 2006*, Bonn, Germany, 3–7 September, pp. 4401/1958, Archive no 440119580813. Code 475P, 813-814, VDI Verlag GmbH, Dusseldorf, Germany.

Hiskakis M, Babou E, Briassoulis D, Marseglia A, Godosi Z and Liantzas K (2008) Recycling specs for agricultural plastic waste (apw) - a pilot test in Greece and in Italy. In: *Proceedings of EurAgEng 2008*, Hersonissos, Crete, 23–26 June 2008, OP-315 (1179322), EurAgEng, Bedfordshire, England.

Hiskakis M, Babou E and Briassoulis D (2011) Experimental processing of biodegradable drip irrigation systems-possibilities and limitations. *Journal of Polymers and the Environment* 19: 887–907

Incineration Directive (2000) EN, Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000. *Official Journal of the European Union*, L 28.12.2000; 332:91, L 332/91, 22.11.2008, Commission of τhe European Communities.

Isagro (2011) [Homepage]. Available at: http://www.isagro.com/index.php?option=com_frontpage&Itemid=1 (accessed 19 April 2013).

Jensen MH and Malter AJ (1995) *Protected agriculture – A global review. Chapter 13: Technology transfer between nations*. World Bank Technical Paper No 253. Washington: The International Bank for Reconstruction and Development.

Kafrit (2011) [Homepage]. Available at: http://www.kafrit.com (accessed 19 April 2013).

Kittas C, Katsoulas N, Katsoupa M and Papaioannou CH (2012) Test of a Test of a Greenhouse Covered by Polyethylene Film that Reflects Near-Infrared Radiation. *Acta Horticulturae* (ISHS) 956: 507–513.

Kumar KS, Tiwari KN and Jha MK (2009) Design and technology for greenhouse cooling in tropical and subtropical regions: A review. *Energy and Buildings* 41: 1269–1275.

Kyrikou I and Briassoulis D (2007) Biodegradation of agricultural plastic films - A critical review. *Journal of Polymers and the Environment* 15: 125–150.

LabelAgriWaste (2006–2009) Labelling agricultural plastic waste for valorising the waste stream. Available at: http://LabelAgriWaste.aua.gr (accessed 16 October 2013).

Laverde G (2002) Agricultural films: types and applications. *Journal of Plastic Film and Sheeting* 18: 269–277.

Leja K and Lewandowicz G (2010) Polymer biodegradation and biodegradable polymers – a review. *Polish Journal of Environmental Studies* 19: 255–266.

Levitan L and Barros A (2003) Recycling agricultural plastics in New York State. *Executive summary*. 2nd Edition. New York: Environmental Risk Analysis Program, Cornell University. Available at: http://www.cfe.cornell.edu/erap/C&ER/PlasticsDisposal/AgPlasticsRecycling/.

Liantzas K, Briassoulis D and Hiskakis M (2007) Comparative analysis of the European and Greek legislative framework for Agricultural Plastic Wastes (APW) and its implementation in Greece. In: *Proceedings of the first conference on environmental management, engineering, planning and* *economics (CEMEPE 2007)*, A Kungolos, K Aravossis, A Karagiannidis, et al (eds). Skiathos, Greece, June 24-28, 2007, pp. 2791–2796.

Martin-Closas L and Pelacho AM (2011) Agronomic potential of biopolymer films, biopolymers - new materials for sustainable films and coatings. In:Plackett D (ed) *B*iopolymers, pp. 354. Chichester: John Wiley Sons.

Martin-Closas L, Picuno P, Rodriguez D and Pelacho AM (2008) Properties of new biodegradable plastics for mulching, and characterization of their degradation in the laboratory and in the field. *Acta Horticulturae (ISHS)* 801:275–282.

Masterpack (2013) [Homepage]. Available at: http://www.masterpaklb.com (accessed 16 October 2013).

Mumtaz M and George J (1995) *Toxicological Profile for Polycyclic Aromatic Hydrocarbons*. Public Health Service, Agency for Toxic Substances and Disease Registry, US Department of Health and Human Services, Atlanta, Georgia.

Nayak PL (1999) Biodegradable polymers: Opportunities and challenges. *Journal of Macromolecular Science, Reviews in Macromolecular Chemistry and Physics* 39: 481–505.

Napco Modern Plastic Products Company - Sack Division (2013) [Homepage]. Available at: http://www.napcomodern.com/sack-Division/Silage-Cover.html (accessed 16 October 2013).

Nitroerg (2011) [Homepage]. Available at: http://www.nitroerg.pl/index.php?section=produkty&parentCategoryId=59&id_produktu=30 (accessed 19 April 2013).

Norres Industrial Hoses (2011) [Homepage] Available at: http://www.norres.com/(accessed 19 April 2013).

Novamont (2013) [Homepage]. Available at: http://www.materbi.com (accessed 19 April 2013).

O2inWines International Association (2011) [Homepage]. Available at: http://www.o2inwines.org/ARTENIUS-PET-PACKAGING-EUROPE.html (accessed 19 April 2013).

Orhan Y and Buyukgungor H (2000) *Enhancement of biodegradability of disposable polyethylene in controlled biological soil*. Environmental Engineering Department, Ondokuz Mayis University, Turkey.

PATI S.p.A (2010) (Personal communication) [Homepage]. Available at: http://www.pati-films.com/en/products/products_for_agriculture/products-for-agriculture-d76.html (accessed 19 April 2013).

Plastics Europe, Association of Plastics Manufacturers (2011) [Homepage]. Available at: http://www.plasticseurope.org/ and http://www.plasticseurope.org/use-of-plastics/agriculture.aspx (accessed 19 April 2013).

Plastika Kritis SA (2011) [Homepage]. Available at: http://www.plastikakritis.com/ (accessed 19 April 2013).

Ren X (2003) Biodegradable plastics: a solution or a challenge? *Journal of Cleaner Production* 11: 27–40.

Revised Waste Framework Directive (2008). EN, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (text with EEA relevance, including directive on Hazardous Waste (91/689/EEC)), *Official Journal of the European Union*, L 312/3, 22.11.2008, Commission of the European Communities

RKW SE (2011) [Homepage]. Available at: http://www.rkw-group.com/home.html (accessed 19 April 2013).

Robinson DW (1991) Development in Plastic Structures and Materials for Horticultural Crops, Food and Fertilizer Technology Center for the Asian and Pasific Region. Available at: http://www.agnet.org/library.php?func=view&id=20110729171201 (accessed 16 October 2013).

Rudnik E and Briassoulis D (2011) Comparative Biodegradation in soil behaviour of two biodegradable polymers based on renewable resources. *Journal of Polymers and the Environment* 19: 18–39.

Scarascia-Mugnozza G, Picuno P and Sica C (2005) [Problems concerning disposal of plastic films after their use]. Bari: Giornata Tecnologica AIM.

Sonnevera International Corporation (2011) Ontario agricultural waste study: environmental impacts of open-burning agricultural plastics. Available at: http://www.cleanfarms.ca/documents/studies/AgPlasticEnviroImpactOpenBurning_FINAL_201107.pdf (accessed 19 April 2013).

Taiganides EP (1979) Wastes are resources out of place. *Agricultural Wastes* 1: 1–9.

Tarapac SA (2011) [Homepage]. Available at: http://www.tarapac.com/en/index.php?page=containers-ibc (accessed 19 April 2013).

The Landfill Directive (1999) EN, Council Directive 1999/31/EC of 26 >April 1999 on the landfill of waste, *Official Journal of the European Union*, L 16/07/1999;182:0001e19, L 182/1, 22.11.2008, Commission of the European Communities.

Thrace Plastics (2011) [Homepage]. Available at: http://www.donlow.gr/, http://www.donlow.gr/el/Index.cfm?get=ir&show=analyst (accessed 19 April 2013).

Two Wests and Elliott SA (2011) Quality equipment for greenhouse and garden. Available at: http://www.twowests.co.uk/TwoWestsSite/category/PLANTPRO_FABRNETS.htm (accessed 19 April 2013).

von Elsner B, Briassoulis D, Waaijenberg D, et al. (2000) Review of structural and functional characteristics of greenhouse in European Union countries: Part I. Design requirements. *Journal of Agricultural Engineering Research* 75: 111–126.

UNIBAS (Università degli Studi della Basilicata) [Homepage]. Available at: http://www.unibas.it (accessed 19 April 2013).

US Environmental Protection Agency. Dioxins and Furans. Washington, DC.: Office of Pollution Prevention and Toxics; http://www.epa.gov/osw/hazard/wastemin/minimize/factshts/dioxfura.pdf (accessed 16 October 2013)

USEPA (2001) US Environmental Protection Agency. Dioxins and Furans. Washington, DC: Office of Pollution Prevention and Toxic. Available at: http://www.epa.gov/osw/hazard/wastemin/minimize/factshts/dioxfura.pdf (accessed 16 October 2013).