Chapter 1
Biomass Categories

Augustina Ephraim, Patricia Arlabosse, Ange Nzihou,
Doan Pham Minh and Patrick Sharrock

Abstract Biomass resources for the production of renewable energy, chemicals and polymeric materials are abundant. In this chapter, these resources will be categorized into woody biomass, agricultural residues and waste, municipal solid waste, sewage sludge and aquatic plants. The origins, use and typical composition (physical, chemical and biological) of the different biomass types will be presented.

1.1 Introduction

Biomass refers to organic materials that are derived from plants or animals, i.e. all materials of biological origin that are not fossilized [1, 2]. Biomass may be divided into two broad groups [3]: virgin biomass includes terrestrial biomass (e.g. trees, crops, vegetables and fruits) and aquatic biomass (e.g. algae and water plants).

Waste includes municipal waste (municipal solid waste (MSW), sewage sludge, landfill gas), agricultural waste (livestock, manure, agricultural crop residue) and industrial wastes (e.g. demolition wood, waste oil or fat).

Traditionally, biomass in the form of fuelwood, agricultural residues and animal dung has been used by society for thousands of years as a source of energy for cooking and heating. The majority of households in the developing world continue to rely on such biomass for cooking as shown by Table 1.1 [4].

"Modern" use of biomass can be divided into four major categories [3]:

- Chemicals such as methanol, fertilizer and synthetic fiber
- Energy such as heat
- Electricity
- Transportation fuel such as gasoline and diesel.

A. Ephraim (✉) · P. Arlabosse · A. Nzihou · D. Pham Minh · P. Sharrock
RAPSODEE CNRS, UMR-5302, Université de Toulouse, IMT Mines Albi,
Campus Jarlard, 81013 Albi Cedex, 09, France
e-mail: aug.ephraim@gmail.com

A. Nzihou (ed.), *Handbook on Characterization of Biomass,*
Biowaste and Related By-products, https://doi.org/10.1007/978-3-030-35020-8_1

Table 1.1 Estimated biofuel consumption, by region (Tg/year)

Region	Fuelwood	Crop residues	Dung	Charcoal
North America	41	0	0	0
Latin America	80	0	0	16
Africa	371	52	0	14
Europe	147	0	0	0
South Asia	344	76	75	3
East Asia	193	323	0	0
Southeast Asia	164	43	0	6
Oceania	10	0	0	0
World	1351	495	75	39

Reproduced with permission from Wiley [4]

Figures 1.1 and 1.2 present some of the thermal, chemical and biological processes involved in converting biomass into useful energy and chemical products [5, 6].

Over the last few decades, waste management has become a major issue in most developed and developing countries. According to a recent World Bank report, 1.3 billion tonne per year of municipal solid waste (MSW) is currently generated worldwide and is expected to double by the year 2025 [1]. As this high level of waste production results in significant economic and environmental costs, many countries, particularly in Europe, have set goals to become “Recycling Societies”—one that does not only avoid producing waste but also uses it as a resource [7]. To achieve this, a number of European Directives have been introduced which aim to increase levels of recycling and recovery rates as well as the production of renewable energies from waste in order to minimize the amount of landfilled waste, thus minimizing greenhouse gas emissions [8, 9]. The main areas of legislation that are considered important for this chapter are [10, 11]:

- The Renewables Directive, RED (2009/28/EC); which is designed to help states progress towards meeting the EU 2020 target of 20% energy derived from renewable sources. According to the directive, eligible feedstocks include the biodegradable fraction from industrial and municipal wastes and residues from agriculture and forestry.
- The Landfill Directive, (1999/31/EC); enforces targeted reduction of biodegradable waste in landfills.
- The Waste Framework Directive, WFD (75/442/EEC); establishes principles of the waste hierarchy—re-duce, reuse, and recycle—to encourage re-use and recycling of waste as well as minimization of waste disposal.
- The Waste Incineration Directive, WID (2000/76/EC); governs the “thermal treatment” of waste, which includes combustion (incineration), gasification and pyrolysis. WID lays out strict specifications on the operating conditions of the thermal facilities (e.g. gas temperature and emission limits).

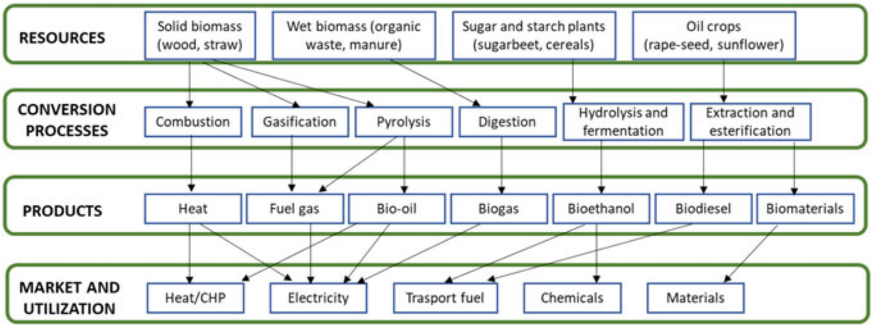
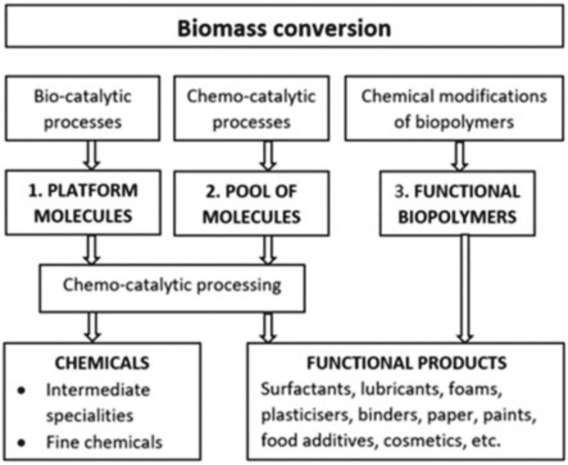


Fig. 1.1 Processes to convert biomass into useful energy and products

Fig. 1.2 Biomass conversion process to chemical and biomaterial products. Reproduced with permission from Chemical Society reviews [6]



These directives have made biowaste valorization more economically attractive and has led to the development of various energy recovery technologies as shown in Table 1.2 [12].

This chapter therefore aims to present the classification of various virgin and waste biomass, with brief discussions on their origin, composition, and valorization processes.

1.2 Woody Biomass

Woody biomass is biomass from trees, bushes and shrubs [13], and can be broadly categorized as (i) forest and plantation wood, (ii) wood processing industry by-products and residues, and (iii) used wood. Figure 1.3 illustrates the various sub-classification of each woody biomass group, which will be discussed in this

Table 1.2 Energy recovery technologies

Established technologies	Type of waste	Product	Application
Anaerobic digestion and hydrolysis	Putrescibles (e.g. Food and animal waste, sewage sludge)	Biogas (methane)	Power generation, fertilizer, cooking gas
Fermentation	Cellulosic waste (e.g. Paper, agro-industrial waste, sewage sludge)	Bio-ethanol	Liquid fuel
Incineration	MSW, RDF, chemicals, clinic waste and sewage sludge	Heat, carbon dioxide, water vapour, ash	Power generation, heating
Emerging technologies			
Gasification and Pyrolysis	RDF, ASR, MSW (for gasification only)	Syngas, pyrolysis oil (bio-oil), char, ash. By-products: metals, chemicals	Transport fuel, chemicals, ammonia and fertilizers, electricity, heat

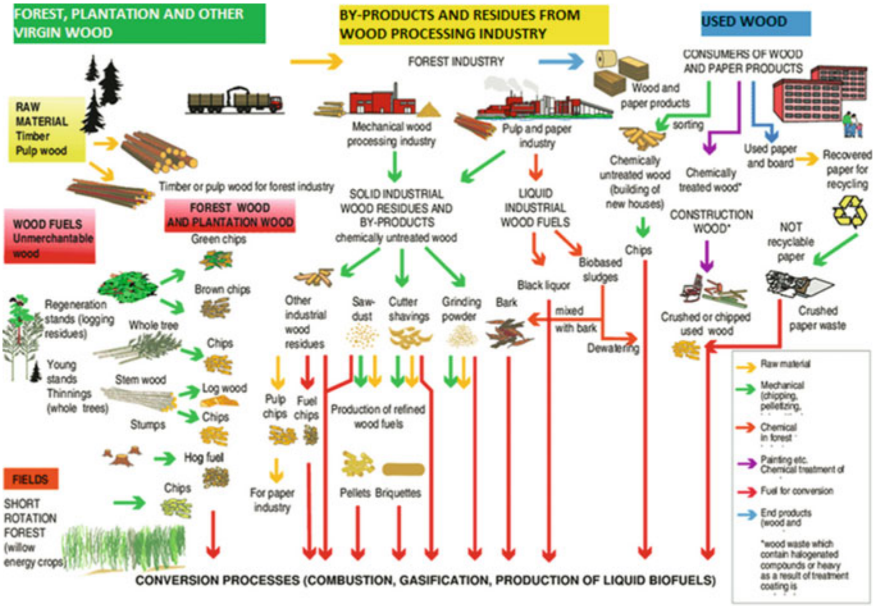


Fig. 1.3 Classification of woody biomass. Reproduced with permission from Springer Nature [13]

section. According to the World Energy Council, woody biomass provides about 90% of the primary energy annually supplied (56 EJ) by all forms of biomass worldwide [2].

1.2.1 Forest and Plantation Wood

According to a survey by Indufor in the year 2012, the world's total area of industrial fast-growing forest plantations is 54.3 million ha [14]. Figures 1.4 and 1.5 show the breakdown of the forest plantations by region. We can observe that Asia has the largest industrial forest plantations (17.7 million ha), followed by North and Latin America (12.8 million ha, each). In Africa, Oceania and Europe, there are about 5, 3.7 and 2.0 million ha of industrial forest plantations, respectively. The countries with the largest plantation area are the United States (US), China and Brazil, with each having over 5 million ha.

The wood obtained from industrial forest plantations can be grouped into softwood and hardwood. This nomenclature does not necessarily related to the wood density. On one hand, hardwoods are produced by angiosperm trees, which yield flowers and have broad leaves. On the other hand, softwoods are from gymnosperm trees that have needles and exposed seeds, but do not have leaves.

The data presented in Table 1.3 were obtained from a detailed survey of 61 countries on various forest species, summarized here as softwoods (e.g. Douglas fir, pine and spruce.) and hardwoods (e.g. willow, eucalyptus and beech). An estimated 1.4 billion m3 of raw wood were harvested from these planted forests in 2005, about 47% of which was devoted to industrial roundwood (e.g. timber, pulpwood, and chips), 39% to pulp and paper and 10% to bioenergy production [15]. Tables 1.4 and 1.5 display the typical properties of various softwood and hardwood species, respectively.

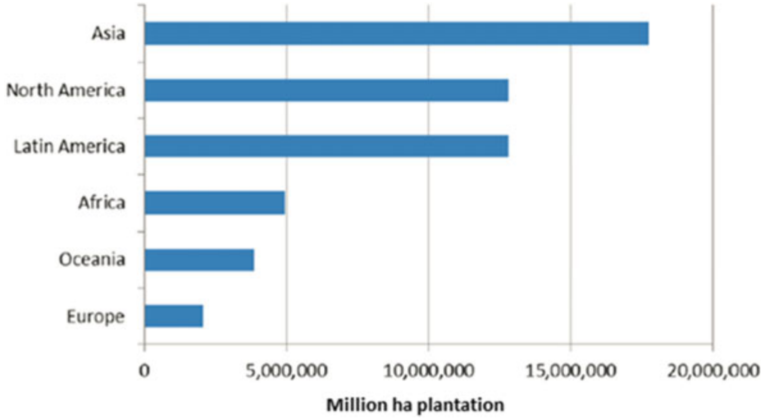


Fig. 1.4 Industrial forest plantations by region, 2012 [14]

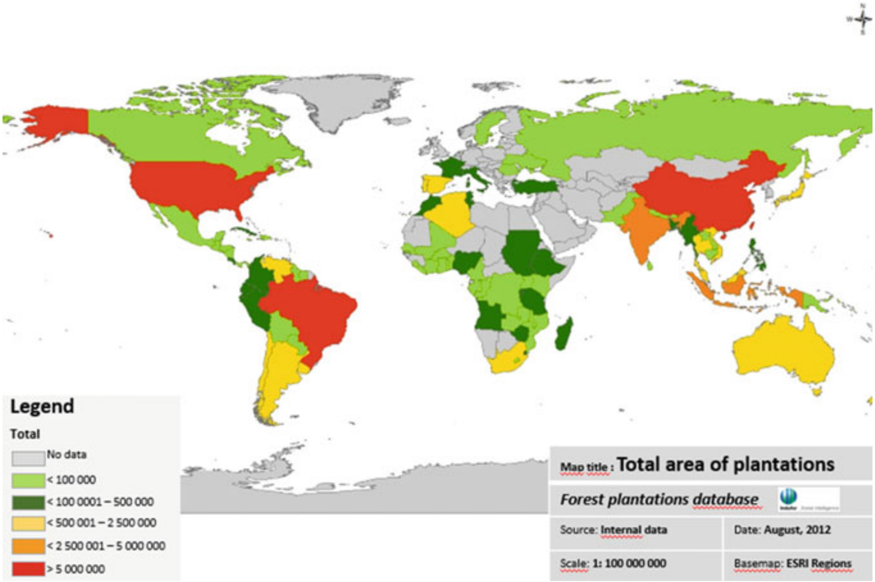


Fig. 1.5 Total area of global industrial forest plantations, 2012 [14]

Table 1.3 Planted forest area, hardwoods and softwoods (million ha)

Region	Softwoods	Hardwoods	Total
Africa	1.7	7.8	9.5
Asia	34.2	90.6	124.8
Northern, Central and Eastern Europe	62.4	12.1	74.5
Southern Europe	4.6	4.7	9.3
North and Central America	26.1	1.7	27.8
South America	5.4	5.6	11.0
Oceania	2.9	0.7	3.6
World	137.3	123.2	260.7

Reproduced with permission from Forest Products Society [15]

1.2.2 Wood Processing By-products and Residues

As shown in Fig. 1.3, the mechanical wood processing industry, as well as the pulp and paper industries, generate solid wood residues (e.g. sawdust, cutter shavings and grinding powder) and liquid wood fuels (e.g. black liquor and bio-based sludges). Refined wood fuels such as pellets and briquettes can be produced from the wood residues for energy purposes.

Table 1.4 Chemical composition of softwood species [16]

Property		Unit	Douglas Fir	Pine	Spruce
Fuel properties					
Proximate analysis	Moisture content	wt% (ar)		8.83	13.05
	Ash content	wt% (dry)	0.48	0.70	0.56
	Volatile matter (VM)	wt% (daf)	84.77	84.26	85.97
	Fixed carbon (100–VM)	wt% (daf)	15.23	15.74	14.03
Ultimate analysis	Carbon	wt% (daf)	52.04	52.01	49.26
	Hydrogen	wt% (daf)	6.30	6.25	5.88
	Nitrogen	wt% (daf)	0.09	0.14	0.13
	Sulphur	wt% (daf)	0.02	0.10	0.02
	Oxygen (calculated by difference)	wt% (daf)	41.55	41.5	44.71
Calorific values	Net calorific value (LHV)	MJ/kg (daf)	19.47	19.36	18.43
	Gross calorific value (HHV)	MJ/kg (daf)	20.95	20.68	19.79
Chemical analyses					
Halides	Chlorine (Cl)	mg/kg (daf)		602.7	66.7
Ash composition	CaO	wt% (ash)	37.08	27.56	36.43
	SiO_2	wt% (ash)	12.26	36.20	18.48
	K_2O	wt% (ash)	17.00	7.57	9.48
	SO_3	wt% (ash)	11.20	1.62	
	MgO	wt% (ash)	5.86	3.26	3.72
	Fe_2O_3	wt% (ash)	4.24	2.74	1.29
	Al_2O_3	wt% (ash)	2.83	6.86	1.50
	P_2O_5	wt% (ash)	1.86	3.39	3.16
	Na_2O	wt% (ash)	3.16	0.67	0.39
	TiO_2	wt% (ash)	0.08	0.12	
	Mn	mg/kg (ash)		7745.0	
	Cu	mg/kg (ash)		241.7	523.8
	Pb	mg/kg (ash)		234.0	25.0
	Cr	mg/kg (ash)		70.0	127.0
	Cd	mg/kg (ash)		10.0	0.9
	Hg				1.2

ar as received basis
daf dry ash-free basis

According to IEA Bionergy, in the year 2008, the estimated global production of wood pellets was 11.5 megatonnes (Mt) and the estimated amount traded was 4 Mt [17]. With an average energy density of 17.5 gigajoules (GJ) per tonne, this amounts to 200 terajoules (TJ) produced and 70 TJ traded.

Table 1.5 Chemical composition of hardwood species [16]

Property		Unit	Willow	Eucalyptus	Beech
Fuel properties					
Proximate analysis	Moisture content	wt% (ar)	12.77	11.10	11.63
	Ash content	wt% (dry)	1.96	1.57	0.67
	Volatile matter (VM)	wt% (daf)	83.54	84.90	83.14
	Fixed carbon (100–VM)	wt% (daf)	16.46	15.10	16.86
Ultimate analysis	Carbon	wt% (daf)	49.80	51.14	48.77
	Hydrogen	wt% (daf)	6.10	6.10	6.02
	Nitrogen	wt% (daf)	0.62	0.27	0.30
	Sulphur	wt% (daf)	0.05	0.04	0.03
	Oxygen (calculated by difference)	wt% (daf)	43.43	42.45	44.88
Calorific values	Net calorific value (LHV)	MJ/kg (daf)	18.49	18.93	17.85
	Gross calorific value (HHV)	MJ/kg (daf)	19.84	20.28	19.16
Chemical analyses					
Halides	Chlorine (Cl)	mg/kg (daf)	152.7	548.2	64.6
	Fluorine (F)	mg/kg (daf)	26.3		4.2
Major elements	Calcium (Ca)	mg/kg (dry)	5408.6	2215.8	2542.8
	Potassium (K)	mg/kg (dry)	2702.2	1584.2	1313.5
	Magnesium (Mg)	mg/kg (dry)	497.9	488.0	409.5
	Phosphorus (P)	mg/kg (dry)	782.4	348.0	98.0
	Silicon (Si)	mg/kg (dry)	445.2	103.0	162.5
	Sodium (Na)	mg/kg (dry)	185.5	454.0	41.9
	Aluminum (Al)	mg/kg (dry)	57.2	91.0	32.5
	Iron (Fe)	mg/kg (dry)	58.0	14.0	68.3
	Titanium (Ti)	mg/kg (dry)	3.6		2.5
Minor elements	Arsenic (As)	mg/kg (dry)	0.7	0.0	1.0
	Cadmium (Cd)	mg/kg (dry)	2.3	0.1	
	Cobalt (Co)	mg/kg (dry)	0.6		12.3
	Chromium (Cr)	mg/kg (dry)	11.1	1.4	2.3
	Copper (Cu)	mg/kg (dry)	6.3	16.0	2.0
	Manganese (Mn)	mg/kg (dry)	12.2	18.0	67.0
	Nickel (Ni)	mg/kg (dry)	23.6	1.3	2.4
	Lead (Pb)	mg/kg (dry)	96.0	0.8	0.9
	Vanadium (V)	mg/kg (dry)	0.2		0.1
	Zinc (Zn)	mg/kg (dry)	98.1	16.0	5.1
	Barium (Ba)	mg/kg (dry)	2.6		16.7
	Mercury (Hg)	mg/kg (dry)	0.1	0.1	
	Selenium (Se)	mg/kg (dry)			1.4
Other elements	Tin (Sn)	mg/kg (dry)	0.7		0.1
	Strontium (Sr)	mg/kg (dry)	14.2		5.2
	Boron (B)	mg/kg (dry)	9.0		4.4
	Antimony (Sb)	mg/kg (dry)	2.9		26.0

(continued)

Table 1.5 (continued)

Property		Unit	Willow	Eucalyptus	Beech
Ash composition	SO_3	wt% (ash)	2.35		
	Cl	wt% (ash)	0.49		
	P_2O_5	wt% (ash)	9.51	29.11	
	SiO_2	wt% (ash)	7.62	17.83	20.00
	Fe_2O_3	wt% (ash)	0.55		1.40
	Al_2O_3	wt% (ash)	1.10	7.87	7.00
	CaO	wt% (ash)	36.47	26.52	26.10
	MgO	wt% (ash)	3.52	7.25	9.20
	Na_2O	wt% (ash)	1.80	4.98	1.80
	K_2O	wt% (ash)	15.98	7.20	23.50
	TiO_2	wt% (ash)	0.05		

1.2.3 Used Wood

Used wood are recovered wood fuels that originate from socio-economic activities outside the forest and wood-processing sectors. Such wastes come from construction sites, demolition of buildings and containers [18]. Used wood may be thermally converted to energy or transformed into chips, pellets, briquettes or powder for recycling purposes.

In Europe, used woods are divided into 3 different classes based on their level of contamination; class A, B and C. Classes A and B are classified under EN 14961-1 (Solid biofuel standard) [19] and class C under EN 15359 (Solid recovered fuel standard) [20]. Table 1.6 provides the typical properties of the classes A, B and C used woods.

Class A

This is virgin wood that has only been mechanically treated. It includes chemically untreated by-products or residues from forest and wood processing industry as well as chemically untreated used wood. Class A wood such as sawmill co-products has a current market as a fuel for co-firing at coal power stations, fuel for other stand-alone biomass plants and raw material for a variety of competing markets, including animal bedding, horticultural use, and, most significantly, the panel board mills [10]. Class A wood is treated as a clean fuel and thus no Waste Incineration Directive (WID) is applied.

Class B

Class B wood is coated, lacquered or otherwise chemically treated wood. Coating does not contain halogenated compounds (for example PVC) and preservatives. Class B includes chemically treated by-products and residues from forest and wood

Table 1.6 Chemical composition of used wood [16]

Property		Unit	Class A	Class B	Class C
Fuel properties					
Proximate analysis	Moisture content	wt% (ar)	13.05	7.38	16.73
	Ash content	wt% (dry)	0.56	2.49	1.77
	Volatile matter (VM)	wt% (daf)	85.97	79.46	79.58
	Fixed carbon (100–VM)	wt% (daf)	14.03	20.54	20.42
Ultimate analysis	Carbon	wt% (daf)	49.26	50.54	53.93
	Hydrogen	wt% (daf)	5.88	5.68	5.95
	Nitrogen	wt% (daf)	0.13	1.44	0.34
	Sulphur	wt% (daf)	0.02	0.06	0.09
	Oxygen (calculated by difference)	wt% (daf)	44.71	42.28	39.69
Calorific values	Net calorific value (LHV)	MJ/kg (daf)	18.43	18.94	19.05
	Gross calorific value (HHV)	MJ/kg (daf)	19.79	20.18	20.41
Chemical analyses					
Halides	Chlorine (Cl)	mg/kg (daf)	66.7	1187.2	316.9
	Fluorine (F)	mg/kg (daf)		22.1	13.4
Major elements	Calcium (Ca)	mg/kg (dry)	6376.6	4050.0	2200.0
	Silicon (Si)	mg/kg (dry)	1790.0	2550.0	2150.0
	Potassium (K)	mg/kg (dry)	1443.7	735.0	285.0
	Magnesium (Mg)	mg/kg (dry)	506.6	450.0	215.0
	Iron (Fe)	mg/kg (dry)	211.4	510.0	2200.0
	Phosphorus (P)	mg/kg (dry)	375.6	100.0	62.5
	Aluminium (Al)	mg/kg (dry)	136.4	455.0	310.0
	Sodium (Na)	mg/kg (dry)	94.0	670.0	250.0
	Titanium (Ti)	mg/kg (dry)	12.3	275.0	2.9
Minor elements	Arsenic (As)	mg/kg (dry)	0.3	8.9	1.3
	Cadmium (Cd)	mg/kg (dry)	0.2	1.3	0.4
	Cobalt (Co)	mg/kg (dry)	0.3	2.2	0.7
	Chromium (Cr)	mg/kg (dry)	2.4	34.5	10.0
	Copper (Cu)	mg/kg (dry)	2.8	21.0	10.2
	Manganese (Mn)	mg/kg (dry)	316.0	76.5	41.5
	Nickel (Ni)	mg/kg (dry)	1.8	4.6	5.6
	Lead (Pb)	mg/kg (dry)	1.7	170.0	81.3
	Vanadium (V)	mg/kg (dry)	0.6	0.8	1.3
	Zinc (Zn)	mg/kg (dry)	41.9	315.0	256.0
	Barium (Ba)	mg/kg (dry)	73.2	345.0	75.1
	Molybdenium (Mo)	mg/kg (dry)	0.1	0.6	
	Selenium (Se)	mg/kg (dry)	0.1	0.2	

(continued)

Table 1.6 (continued)

Property		Unit	Class A	Class B	Class C
Other elements	Tin (Sn)	mg/kg (dry)	0.5	1.1	1.0
	Boron (B)	mg/kg (dry)	7.2		
	Antimony (Sb)	mg/kg (dry)	0.1		1.6
	Boron (B)	mg/kg (dry)		7.4	3.4
	Strontium (Sr)	mg/kg (dry)		17.5	
Ash composition	CO_2	wt% (ash)	23.07	23.07	1.10
	SO_3	wt% (ash)	1.24	1.24	6.58
	Cl	wt% (ash)	0.12	0.12	11.80
	P_2O_5	wt% (ash)	3.16	3.16	18.04
	SiO_2	wt% (ash)	18.48	18.48	13.31
	Fe_2O_3	wt% (ash)	1.29	1.29	4.20
	Al_2O_3	wt% (ash)	1.50	1.50	17.65
	CaO	wt% (ash)	36.43	36.43	3.63
	MgO	wt% (ash)	3.72	3.72	6.21
	Na_2O	wt% (ash)	0.39	0.39	13.44
	K_2O	wt% (ash)	9.48	9.48	
	TiO_2	wt% (ash)			0.52
	Pb	mg/kg (ash)	25.0	25.0	7.0
	Cd	mg/kg (ash)	0.9	0.9	0.0
	Cu	mg/kg (ash)	523.8	523.8	109.0
	Hg	mg/kg (ash)	1.2	1.2	
	Mn	mg/kg (ash)			0.5
	Cr	mg/kg (ash)	127.0	127.0	63.0

processing industry (e.g. furniture, kitchen wood) as well as chemically treated used wood excluding demolition wood. It does not come under WID and thus can be used as a feedstock for industrial wood processing operations, such as the manufacture of panel products including chipboards and fireboards [21]. However as it is difficult to separate out the clean waste wood from the contaminated, in countries like the UK, Class B wood is usually fed to a mass burn incinerator or directly disposed to landfill [10].

Class C

Class C consists of wood that has been coated or treated with halogenated compounds such as PVC but does not contain preservatives. An example of such wood is demolition wood whose origin is difficult to verify. Class C wood, which is classified as a solid recovered fuel according to EN 15359 [20], must be incinerated in compliance with WID.

1.3 Agricultural Residues and Waste

Agricultural waste consists of organic material, such as manure from livestock, slurry, silage effluent and crop residues. Figure 1.6 shows that agricultural and forestry waste is one of the major waste categories generated throughout Europe. Individual countries within Europe show a variation in the arising of agricultural waste due to the different extents of agriculture areas within the economy and different farming methods. Examples of agricultural waste tonnage available in Europe are: Spain, estimated at 114 million tonnes/year; France, 377 million tonne/year; UK, 87 million tonne/year [22]. In this section, we will focus our discussion on crop residues and animal dung.

1.3.1 Crop Residues

Crop residues are organic materials that are left after a crop has been harvested or processed into a usable re-source. These residues include husks, seeds, bagasse, molasses and roots, which are mainly derived from cereals, sugar crops, roots and tubers, vegetables, fruits and oil crops.

The majority of crop residues are landspread, while some are used as animal feed, compost or as fuel for bio-gas production [23]. Other, less frequent uses of crop residues are as building material and sources of extraction of organic compounds [24].

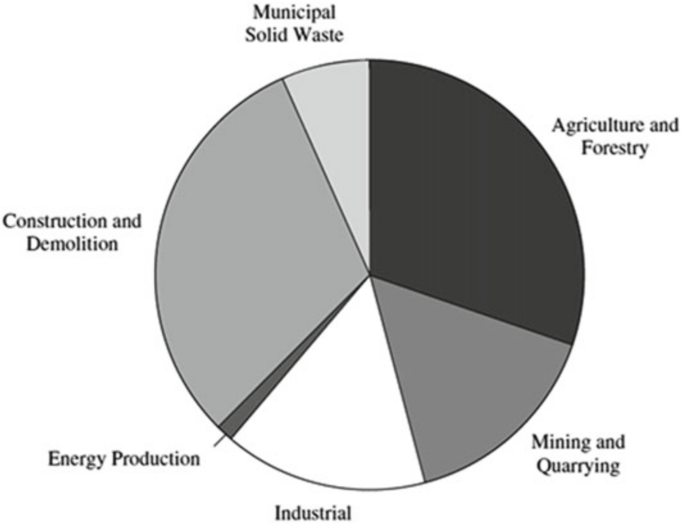


Fig. 1.6 Total waste generated by sector in the EU (15 members 2001) [22]

As shown in Table 1.7, crop residues are usually high in nutrients such as carbon (C), nitrogen (N), phosphorous (P) and potassium (K), and thus can substitute commercial fertilizers for improving crop yields and soil health. It has been reported that the integrated use of crop residues and mineral fertilizer reduces the cost and amount of fertilizer required by the crops [25–27]. Consequently, landspreading is considered to be the best practiced environmental option [28].

Regarding biogas production, crop residues may be suitable fuels if well converted. This is mainly due to their high carbon, hydrogen and volatiles content, as shown in Table 1.7. For example, 1 kg of pre-treated crop waste and water hyacinth has the potential of producing 0.037 and 0.045 m^3 of biogas, respectively [29].

1.3.2 Animal Dung

Animal dung or feces is indigestible plant material released from the intestine of an animal. It is generally used as manure for landspreading or as a fuel source. For these purposes, the most commonly used dung are those derived from cattle (cows and buffaloes), pig and poultry (chickens).

Poultry litter, consisting of a mixture of bird droppings and wood shavings has received interest due to its high generation rates and high calorific value, which therefore makes it more suitable as a fuel than as manure for landspreading [23, 30].

Table 1.7 Chemical composition of various crop residues [16]

Property		Unit	Sugarcane bagasse	Almond shell	Rice husk	Live pits
Fuel properties						
Proximate analysis	Moisture content	wt% (ar)	21.53	10.13	10.60	7.04
	Ash content	wt% (dry)	5.70	2.38	18.03	2.30
	Volatile matter (VM)	wt% (daf)	83.77	78.89	76.95	79.47
	Fixed carbon (100–VM)	wt% (daf)	16.23	21.11	23.05	20.53
Ultimate analysis	Carbon	wt% (daf)	49.57	49.90	46.14	49.89
	Hydrogen	wt% (daf)	5.97	6.15	6.37	6.32
	Nitrogen	wt% (daf)	0.40	0.71	0.90	0.92
	Sulphur	wt% (daf)	0.08	0.03	0.20	0.07
	Oxygen (calculated by difference)	wt% (daf)	43.98	43.21	46.39	42.80
Calorific values	Net calorific value (LHV)	MJ/kg (daf)	17.89	18.55	16.42	20.09
	Gross calorific value (HHV)	MJ/kg (daf)	19.19	19.91	17.79	21.22

(continued)

Table 1.7 (continued)

Property		Unit	Sugarcane bagasse	Almond shell	Rice husk	Live pits
Chemical analyses						
Halides	Chlorine (Cl)	mg/kg (daf)	1030.1	74.6	960.1	663.8
Biochemical composition	Cellulose	wt% (dry)	37.27	35.70	33.70	28.10
	Hemicellulose	wt% (dry)	35.80	28.83	22.00	37.20
	Lignin	wt% (dry)	20.13	28.60	22.83	28.25
Ash composition	SO_3	wt% (ash)	3.57	1.40	0.77	0.56
	P_2O_5	wt% (ash)	3.19	5.57	0.87	2.46
	SiO_2	wt% (ash)	47.23	8.81	89.39	30.82
	Fe_2O_3	wt% (ash)	10.01	2.22	0.40	6.58
	Al_2O_3	wt% (ash)	13.07	1.96	0.22	8.84
	CaO	wt% (ash)	4.56	14.50	1.30	14.56
	MgO	wt% (ash)	3.34	4.77	0.57	4.24
	Na_2O	wt% (ash)	0.80	1.41	0.35	27.80
	K_2O	wt% (ash)	9.97	34.36	5.04	4.40
	TiO_2	wt% (ash)	2.16	0.10	0.02	0.34

Furthermore, it has been shown that composting of poultry dung for land use has its disadvantages including the loss of nitrogen and other nutrients during composting [30]. The poultry litter has higher biogas yield potential than cattle and pig dung, after undergoing anaerobic digestion [29]. This biogas can be used in turn to generate heat for space heating within the farm or to produce electricity. Some characteristics of animal dung have a significant impact on the amount of biogas produced. These characteristics include the carbon/nitrogen (C/N) ratio, volatile matter content, and toxicity [29].

C/N ratio

A C/N ratio between 20 and 30 is considered to be optimum for anaerobic digestion [29]. If the C/N ratio is very high, the nitrogen will be quickly consumed by methanogenic bacteria (methanogens) in order to meet their protein requirements, which will lower their reaction with the left over carbon content of the fuel, and thus lower gas production. However, if the C/N is very low, the excess nitrogen will be re-leased in the form of ammonia (NH4), which may raise pH value of the digester content above 8.5, and therefore create a toxic environment for the methanogens. By observing Table 1.8, the C/N ratio of cow dung is 20 whereas for pig and chicken dung, the C/N ratios are 15 and 8 respectively. For the case where the C/N ratio is significantly low, the fuel can be mixed with those of high C/N ratio, such as crop residues, in order to bring the feedstock pH to a desirable level.

Table 1.8 Chemical composition of animal manure [16]

	Property	Unit	Cow	Pig	Chicken
Fuel properties					
Proximate analysis	Moisture content	wt% (ar)	48.64	56.10	38.10
	Ash content	wt% (dry)	33.38	25.30	24.55
	Volatile matter (VM)	wt% (daf)	83.22	79.06	80.66
	Fixed carbon (100–VM)	wt% (daf)	16.78	20.94	19.34
Ultimate analysis	Carbon	wt% (daf)	47.60	50.30	45.79
	Hydrogen	wt% (daf)	6.66	6.12	6.16
	Nitrogen	wt% (daf)	2.41	3.37	5.72
	Sulphur	wt% (daf)	0.50	0.67	0.92
	Oxygen (calculated by difference)	wt% (daf)	42.83	39.54	41.41
Calorific values	Net calorific value (LHV)	MJ/kg (daf)	19.46	20.05	18.12
	Gross calorific value (HHV)	MJ/kg (daf)	20.91	21.19	19.35
Chemical analyses					
Halides	Chlorine (Cl)	mg/kg (daf)	18,600.6	10,098.6	6251.4
	Bromine (Br)	mg/kg (daf)		7.2	12.2
	Fluorine (F)	mg/kg (daf)		37.6	13.5
Major elements	Aluminium (Al)	mg/kg (dry)		597.8	735.2
	Potassium (K)	mg/kg (dry)	11,300.0	15,290.5	30,013.2
	Sodium (Na)	mg/kg (dry)	2400.0	2771.8	4417.7
	Calcium (Ca)	mg/kg (dry)	5800.0	9841.4	64,079.1
	Silicon (Si)	mg/kg (dry)		5613.6	3817.8
	Magnesium (Mg)	mg/kg (dry)		6037.8	6960.8
	Iron (Fe)	mg/kg (dry)		2208.9	1043.5
	Phosphorus (P)	mg/kg (dry)		9247.1	21,184.2
	Titanium (Ti)	mg/kg (dry)		35.2	34.4
Minor elements	Arsenic (As)	mg/kg (dry)		2.1	
	Cadmium (Cd)	mg/kg (dry)	0.7	0.2	0.2
	Cobalt (Co)	mg/kg (dry)		1.3	1.6
	Chromium (Cr)	mg/kg (dry)	35.0	7.2	19.1
	Copper (Cu)	mg/kg (dry)	56.0	81.0	70.3
	Manganese (Mn)	mg/kg (dry)		232.2	408.6
	Nickel (Ni)	mg/kg (dry)	12.0	6.1	19.6
	Lead (Pb)	mg/kg (dry)	31.0	4.1	3.3
	Vanadium (V)	mg/kg (dry)		2.3	3.7
	Zinc (Zn)	mg/kg (dry)	253.0	324.8	351.2
	Barium (Ba)	mg/kg (dry)		21.6	22.8
	Molybdenium (Mo)	mg/kg (dry)		3.6	5.1
	Selenium (Se)	mg/kg (dry)		1.3	1.4

Volatile matter content

Volatile matter is the organic combustible part of the fuel which is liberated when heated to about 550 °C. In the absence of air, the higher the volatile matter content in a unit mass of fresh dung, the higher the gas production.

Table 1.9 Composition of office paper waste (OP), newspaper waste (NP) and cardboard waste (CB) and Whatman No. 1 filter paper (FP) as reference according to [42]

Parameter	OP	FP	NP	CB
TS (%)	95.3 ± 0.2	95.5 ± 0.1	93.2 ± 0.4	95.4 ± 0.3
VS (% TS)	98.5 ± 0.2	100	96.1 ± 0.3	87.2 ± 0.2
Ash (% TS)	1.4 ± 0.0	None	3.9 ± 0.1	12.8 ± 0.2
Lignin (% TS)	1.4 ± 0.5	None	23.4 ± 0.5	17.8 ± 0.5
Cellulose (% TS)	84.9 ± 1.3	100	68.5 ± 1.1	56.9 ± 0.8
Hemicellulose (% TS)	12.3 ± 0.6	None	13.1 ± 0.3	10.7 ± 0.3
COD (g 0_2/gDM)	1.07 ± 0.02	1.14 ± 0.03	1.21 ± 0.03	1.10 ± 0.02

Reproduced with permission from Elsevier

TS total solids, *VS* volatile solids, *COD* chemical oxygen demand, *DM* dry matter

Toxicity

A high concentration of mineral ions, heavy metals, antibiotics and detergents that may be pre-sent in the animal dung, may inhibit the growth of microbes in the digester [29]. For example, heavy metals such as copper, chromium and nickel, in small quantities are essential for the growth of bacteria but their higher concentrations (i.e. 100, 200 and 200–500 mg/L respectively) have toxic effects. Table 1.9 displays the typical mineral and heavy metal contents of animal dung.

1.4 Municipal Waste

According to the European Commission [31], municipal waste is defined as below: “Municipal waste covers household waste and waste similar in nature and composition to household waste”.

However, European Commission specifies that this definition has evolved over time by formalizing it along the 3 main dimensions for waste statistics: waste origin, waste materials and waste collectors. More details can be found elsewhere [31].

According to the EEA Report No. 2, 2013 [2], municipal waste is defined as below:

> Municipal waste is mainly produced by households, though similar wastes from sources such as commerce, offices and public institutions are included. The amount of municipal waste generated consists of waste collected by or on behalf of municipal authorities and disposed of through the waste management system.

According to the EU’s Landfill Directive, municipal solid waste is defined as “waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households” [32, 33].

U.S. Environmental Protection Agency considers that “Municipal Solid Waste (MSW)—more commonly known as trash or garbage—consists of everyday items we use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, schools, hospitals, and businesses" [34].

From these definitions, it appears that municipal wastes can be listed as: food and kitchen waste; green waste (yard trimmings); wood and wood-based materials; paper; cardboard; glasses; plastics; metals; rubber and leather; textiles; and miscellaneous inorganic wastes. Among these wastes, food and kitchen waste; green waste (yard trimmings); wood and wood-based materials; paper; cardboard can be regrouped in the category of biowaste considering their non-fossil origin. Thus, municipal waste is generally a very complex medium which contains various components. Study on municipal waste needs specific conventions and definitions. For example, there are different methods for the analysis of municipal waste composition, which depend on the organism or country considered, as previously reviewed by Lisa and Anders [35].

The nature and the generation rate of municipal waste vary geographically as a function of continent, region, country and even department/state of each country. It depends on several factors such as income level, living standards, economic activities, urbanization rate, local regulation rules etc.

The next section will address some general statistics on municipal waste generation as well as its evolution with time. According to the World Bank [36], in 2012, the total amount of municipal solid waste generated in the world reached about 1.3 billion ton per year, amounting to a footprint of 1.2 kg per person per day. The generation of MSW by region is as follows (million ton of municipal waste per year):

- The organization for economic co-operation and development (OECD) countries [37]: 572.
- South Asia: approximately 70.
- East Asia and the Pacific Region: approximately 270.
- Eastern and Central Asia: at least 93.
- Sub-Saharan Africa: approximately 62.
- Middle East and North Africa: 63.
- Latin America and the Caribbean: 160.

Because of the rapid evolution of world population, the World Bank foresees that the total amount of MSW can reach 2.2 billion tons per year by 2025.

Figure 1.7 shows the amount of municipal waste generated in 32 European countries from 2001 to 2010 as well as the management of the waste. It is evident that the total amount of municipal waste in these countries did not significantly evolve during this decade. However, the management remarkably changed with the reduction of landfill and the increase of incineration and recycling fractions. The average amount of municipal waste generated per capita during this decade varied strongly between countries, from around 300 kg per capita in Latvia, Estonia, Poland, Slovakia to around 520 kg per capita in France, Spain, Germany or even around 700 kg per capita in Cyprus and Switzerland [32].

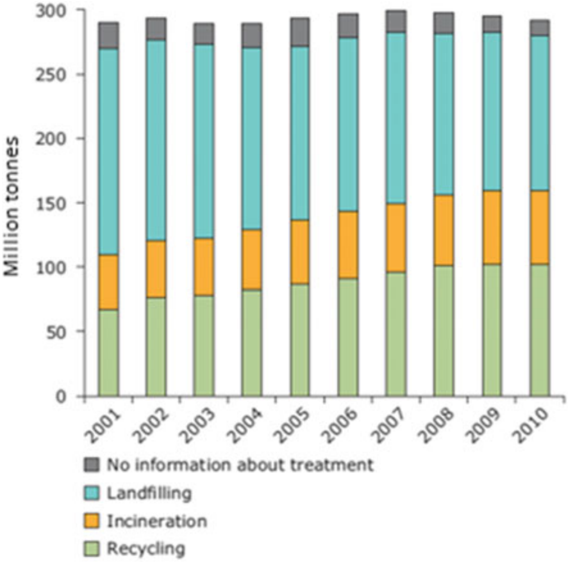


Fig. 1.7 Municipal waste amount and management in 32 European countries, 2001–2010 [32]

China is known as the country having the highest population these last decades. In parallel with its population evolution, urbanization and living standards in China have evolved quickly which has had an impact on the generation of municipal waste and its treatment in this country. Cheng and Hu [38] reported the total amount of municipal solid waste collected and treated in China during 1980–2005 period with estimates made for the 2010–2015 period (Fig. 1.8). The amount of collected MSW in this country was increased by a factor of roughly 2 for every 10 years lap. The World Bank reported also that the total municipal waste in China reached around 190 million tons per year in 2010s [36].

The evolution of MSW generation in USA from 1960 to 2014 linearly in-creased up to 2000s [39]. Then, it was practically unchanged around 250 million tons per year for 2000–2014 period. In parallel, a continuous increase was observed for the average amount of MSW generated per capita per year from 1960 to 1990s. Then, this average amount was stagnated around 750 kg per year.

In the case of France, the average amount of municipal waste generated per capita per year reached around 570 kg during the last 15 years. In 2011, 38.5 million tons of household waste and similar waste were collected and sent to treatment and valorization plants. Note that household waste represents around 80% and similar waste occupies around 20%. About the composition of household waste, a national campaign on the characterization of this waste was carried out in 2007 by ADEME [40] and the results are shown in Fig. 1.9. Its composition did not significantly evolve from 1993 to 2007. It is worth noting that putrescible wastes, paper and paperboard represent around 55% of the total household waste generated. In the case of UK, paper and cardboard wastes represent 23.6% of the household waste generated during the year for 2001–2003 period while kitchen and garden wastes represent 35.1%, which were close to the case of France [41].

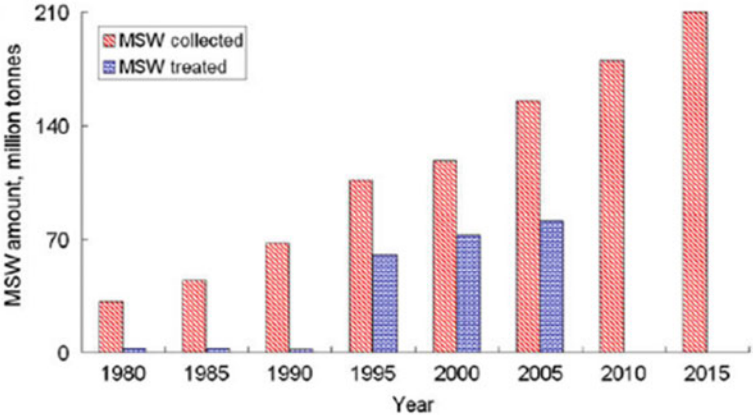


Fig. 1.8 Municipal solid waste collected and treated in China. Reproduced with permission from Elsevier [38]

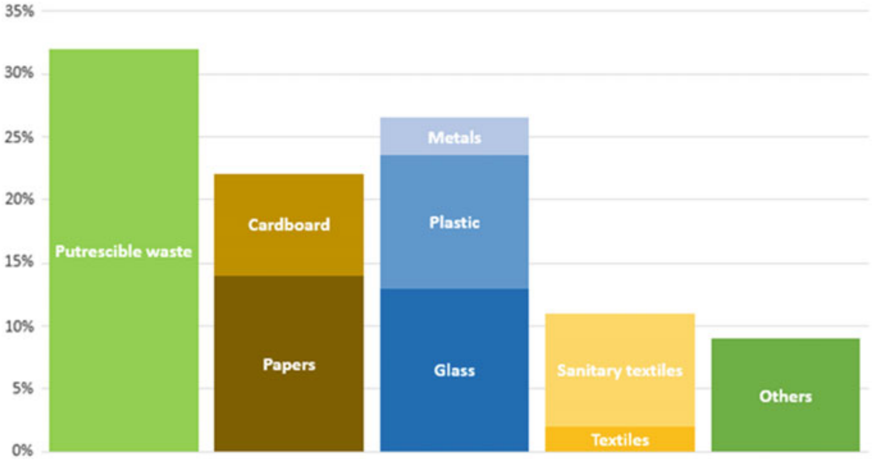


Fig. 1.9 Composition of household waste in France according to a characterization. Adapted from ADEME [40]

The evolution of paper and cardboard wastes, food wastes and garden wastes in USA is presented in Fig. 1.10 [37]. The quantity of these wastes increased up the year 2000. Then they stagnated, or even decreased in the case of paper and cardboard wastes, which probably due numerical developments. These three kinds of wastes represented around 55% of the total amount of municipal waste in USA during the last decade. This is comparable to European countries, i.e. France or UK. Taking into account the forecast of the World Bank, the total amount of paper and cardboard, food waste and garden waste may reach 1.2 billion of ton by 2025.

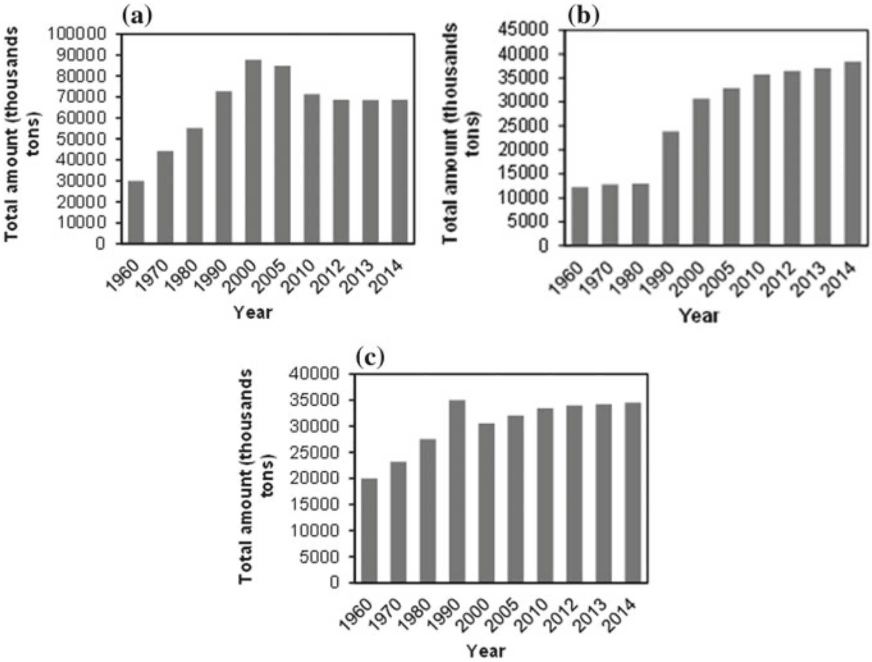


Fig. 1.10 Evolution of paper and cardboard wastes (**a**), food wastes (**b**) and garden wastes (**c**) in USA

Garden waste generally has the typical composition of woody biomass, which is presented in Sect. 1.2. Paper and cardboard are fabricated from woody biomass with various compositions of cellulose, hemicellulose and lignin. In general, lignin content in these wastes increases by the following order: office paper waste content < newspaper waste < cardboard. For example, Yuan et al. [42] reported the composition of these paper and cardboard wastes.

The composition of food waste is much more complex compared to paper and cardboard wastes. Food waste has local, seasonal and punctual properties and the composition can be very variable between continent, country, urbanization level etc. As example, a recent study in UK [43] shows that food waste generation per household per year increased by the following order (for 2008–2012 period): January to March < April to June < October to December < July to September. Other factors which influence on the food waste generation in UK are: levels of deprivation, region and nation, and population density. In another report, the Waste and Resources Action Programme (WRAP) reported the results from a wide survey of municipal waste of the Wale during 2009 [44]. The objective was to fully characterize food waste before their anaerobic digestion. The results obtained were as follows:

- Solid content: varied from around 20–34 wt% depending on the community. Also, food waste generated during winter had more solid content than during summer.
- Total carbohydrate content: varied from around 35–135 g/kg during summer and around 100–210 g/kg during winter, depending on the community exanimated. Large standard deviation was observed due to the heterogeneity of samples and the difficulty to homogenize samples.
- Lipid content: varied from around 8–130 g/kg during summer and around 25–110 g/kg during win-ter. Large standard deviation was observed.
- Protein content: varied from around 10–150 g/kg during summer and around 20–80 g/kg during winter. Large standard deviation was observed.
- CHNSO: The content of C, O, H, N and S were found to be approximately 48, 39, 7, 3 and <1 wt%, respectively.

1.5 Sewage Sludge

To protect public health and the environment, the water that is of no immediate value to the purpose for which it was used or in the pursuit of which it was produced, e.g. wastewater, has to be collected and treated in wastewater treatment plants (WWTPs) before being released to the environment. A wide variety of processes are available and provide different levels of wastewater treatment, known as preliminary, primary, secondary and advanced/tertiary treatments [45]. These treatments produce several inevitable by-products, including screenings, grit, scum and sewage sludges. Of all these constituents, sewage sludges are by far the largest in volume. Contaminants initially present in the wastewater, e.g. heavy metals, hazardous air pollutants (HAPs) and PCBs, are concentrated in the sludges.

In developed countries, one considers that the treatment of the wastewater of one so-called 'population equivalent' or PE, produces annually between 12 and 31 kg of sludge, expressed on dry basis [46, 47]. However, the amount of sludge produced depends on many factors, including the composition and volume of the incoming wastewater as well as the type of treatment processes implemented in the WWTPs, and hence is quite variable. Thus, for example, per capita annual sludge production in China was only 4.5 kg in 2013 [48]. Regional discrepancies between old (EU-15) and new European states (EU-12) members are al-so reported in the European Community [49]. Differences are due to variations in percentages of population served by centralized wastewater treatment plants, variation in influent characteristics (for instance, Chinese influents are characterized by particularly low chemical oxygen demand), treatments applied in the WWTPs as well as contribution of the industrial sectors. Accordingly, the total amount of urban sludge annually generated on a dry basis was around 6.25 million tons in China in 2013 [48], 10.9 million tons for EU-27 countries in 2005 [49] and 7.18 million of biosolids[1] in 2004 [51]. Throughout the world, stringent regulation, higher wastewater treatment coverage and implementation of advanced treatment processes will increase significantly the annual sewage sludge production.

As highlighted in Table 1.10, raw sludges contain a large amount of water, up to 98% for a secondary sludge, and high levels of organic matter. Furthermore, sludges are nutrient rich materials [52], including macronutrients (especially N, P, K, Ca, S and Mg) and micronutrients (such as Fe, B, Mn, Zn, Cu, Ni) that are essential for plant growth and plant metabolism.

Varieties of technologies are available to reduce the volume (thickening, conditioning, mechanical and/or thermal dewatering) and improve the quality (anaerobic or aerobic digestion, composting or liming). Choice and combination are closely related with the final disposal practices (Fig. 1.11). Obviously, the size of the WWTP is a key driver for the selection of an appropriate technology. For instance, due to a high capital cost, thermal drying is usually implemented in big WWTPs (PE > 100,000). However, solar dryers constitutes a good alternative to thermal dryer for small to medium size WWTPs, i.e. between 2000 and 50,000 PE.

To comply with the waste management hierarchy, full recycling of the organic matter, on condition that potential risks associated with the presence of pollutants are effectively managed, is widespread world-wide (Fig. 1.12). More or less stringent limits regarding storage of sewage sludge have been introduced in most countries, progressively restricting the amount of sewage sludge and organic wastes sent to landfills (Fig. 1.13). However the nature of the sludge, rich in nutrients but also loaded with mineral and organic contaminants, has led countries to seek different pathways for sludge disposal. In the coming decades, changes in regulations could negatively influence agricultural reuse. The most probable developments will concern possible controls on pathogen content, protection of human health and the environment from risks that can be posed by chemicals (new European REACH[2] regulation) and incentives on renewable energy. Anaerobic digestion of sewage sludge or co-digestion of sludge with food waste, organic fraction of municipal solid wastes or agricultural by-products for energy recovery is encouraged in many countries.

In developed countries, the cost related to sludge processing and management accounts for 50% of the whole operation expenses at the wastewater treatment plant, 30% of the total electricity consumption and up to 40% of the total wastewater treatment emissions [51]. Accordingly, sludge management remains one of the most complex environmental, technical, financial and regulatory challenges.

---

[1] Two different terms have been used historically: after proper treatment and processing to meet U. S. Environmental Protection Agency, sewage sludges were referred to as biosolids [50]. Consequently, biosolids do not represent the total resources. Nowadays, both terms are often used interchangeably.

[2] ***R****egistration*, **E**valuation, **A**uthorisation and restriction of **CH**emicals.

Table 1.10 Composition of municipal sewage sludge [53]

Parameter	Type of sludge		
	Untreated primary sludge	Digested primary sludge	Secondary sludge
Total dry solids (% of TS)	2.0–8.0	6.0–12.0	0.8–**1**.2
Volatile solids (% of TS)	60–80	30–60	59–88
Grease and fats (% of TS)	7–35	n/a	5–12
Protein (% of TS)	20–30	15–20	32–41
Cellulose (% of TS)	8.0–15.0	8.0–15.0	7–9.7
Phosphorus (% of TS)	0.8–2.8	1.5–4.0	2.8–11.0
Nitrogen (% of TS)	1.5–4	1.6–6.0	2.4–5.0
Potassium (% of TS)	0–1	0–3.0	0.5–0.7
pH	5.0–8.0	6.5–7.5	6.5–8.0

Reprinted with permission from Elsevier
n/a data not available, *TS* total solids

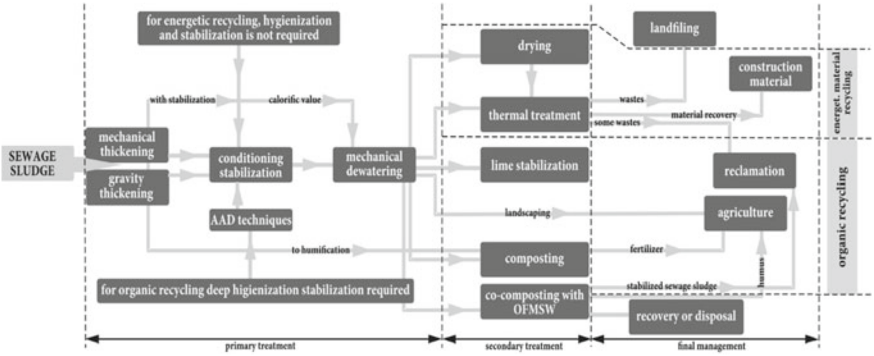


Fig. 1.11 Alternatives for the sewage sludge treatment and disposal strategies (AAD: Advanced aerobic digestion, OFMSW: Organic fraction of municipal solid waste). Reprinted with permission from Elsevier [53]

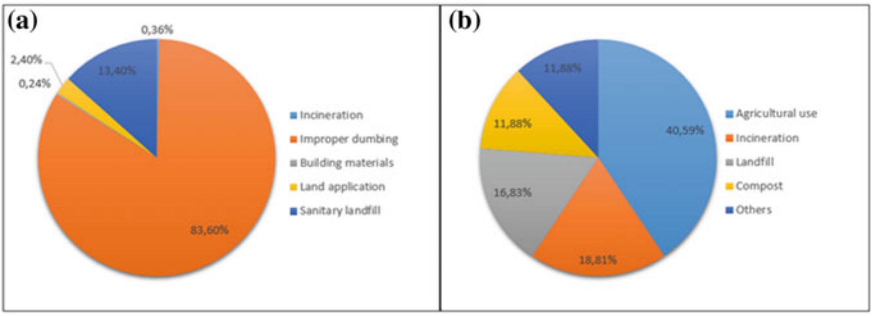
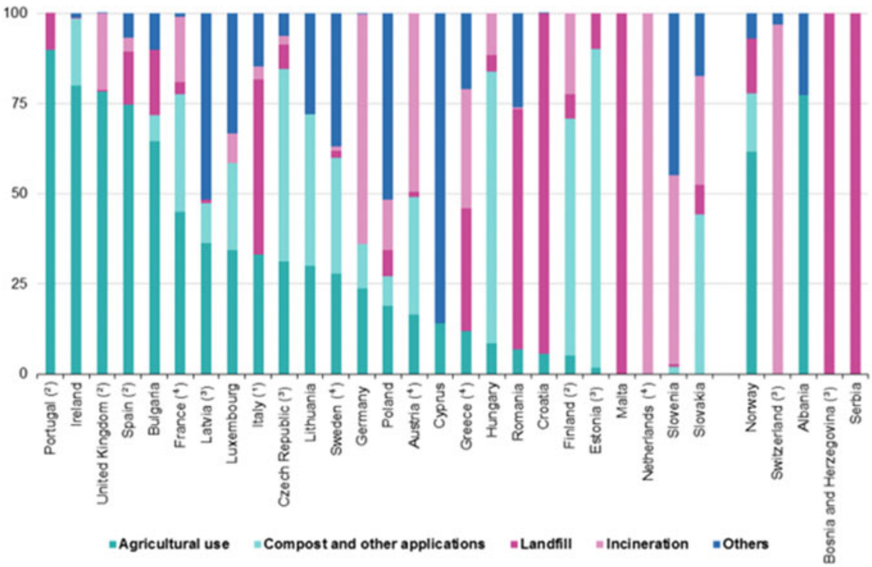


Fig. 1.12 Situation of sludge disposal (**a**) in China in 2013 [48] and **b** EU-27 in 2005 [49]



Note: Belgium, Denmark: not available
(1) 2010 data
(2) 2012 data
(3) 2013 data
(4) 2014 data

Fig. 1.13 Situation of sludge disposal in EU countries in 2015

1.6 Microalgae and Aquatic Plants

Photosynthetic autotrophs or phototrophs are organisms that can convert light energy into chemical energy and food. Algae and aquatic plants are important autotrophs that thrive in aquatic environments (shallow coastal zones, wetlands, rivers, lakes and oceans) and provide food and habitat for other organisms. A key difference between these two autotrophs is that aquatic plants have a vein-like vascular system whereas algae generally don't [54]. This section will provide a general analysis of the key characteristics and use of microalgae and aquatic plants.

1.6.1 Microalgae

Microalgae are microscopic organisms that live in salt or fresh water. The three most important classes of microalgae in terms of abundance are the diatoms (Bacillariophyceae), the green algae (Chlorophyceae), and the golden algae (Chrysophyceae) [55]. These species store energy in the form of oils, carbohydrates and proteins as shown in Table 1.11.

Table 1.11 Chemical composition of algae on a dry matter basis (%) [55]

Species of a sample	Proteins	Carbohydrates	Lipids	Nucleic acid	Oil content
Anabaena cylindrica	43–56	25–30	4–7	–	–
Botryococcus braunii	–	–	–	–	25–75
Chlamydomonas rheinhardii	48	17	21	–	–
Chlorella pyrenoidosa	57	26	2	–	–
Chlorella sp.	–	–	–	–	28–32
Chlorella vulgaris	51–58	12–17	14–22	4–5	–
Crypthecodinium cohnii	–	–	–	–	20
Cylindrotheca sp.	–	–	–	–	16–37
Dunaliella bioculata	49	4	8	–	–
Dunaliella primolecta	–	–	–	–	23
Dunalierlla salina	57	32	6	–	–
Euglena gracilis	39–61	14–18	14–20	–	–
Isochrysis sp.	–	–	–	–	25–33
Monallanthus salina	–	–	–	–	>20
Nannochloris sp.	–	–	–	–	20–35
Nannochloropsis sp.	–	–	–	–	31–68
Neochloris oleoabundans	–	–	–	–	35–54
Nitzschia sp.	–	–	–	–	45–47
Phaeodactylum tricornutum	–	–	–	–	20–30
Porphyridium cruentum	28–39	40–57	9–14	–	–
Prymnesium parvum	28–45	25–33	22–38	1–2	–
Scenedesmus dimorphus	8–18	21–52	16–40		–
Scenedesmus obliquus	50–56	10–17	12–14	3–6	–
Scenedesmus quadricauda	47	–	1.9	–	–
Schizochytrium sp.	–	–	–	–	50–77
Spirogyra sp.	6–20	33–64	11–21	–	–
Spirulina maxima	60–71	13–16	6–7	3–4.5	–
Spirulina platensis	46–63	8–14	4–9	2–5	–
Synechoccus sp.	63	15	11	5	–
Tetraselmis maculata	52	15	3	–	–
Tetraselmis sueica	–	–	–	–	15–32

Adapted with permission from Elsevier

Biomass from microalgae has many applications. The usual methods by which microalgae biomass is cultivated, harvested, processed and converted into useful products [56]. Such products include biofuels (e.g. biodiesel, biomethane and bioethanol), nutritional supplements, fertilizers, and phytoremediation media.

1.6.2 Aquatic Plants

Aquatic plants use the sun's energy and carbon dioxide in the atmosphere to produce starch and sugar via photosynthesis. These plants are known for their high productivity levels, photosynthetic efficiencies, as well as the wide range of chemicals they produce [56]. Since they grow in wetlands, aquatic plants do not compete for land that could be used for growing crops or forests [57]. Of the many aquatic plants that exist, Cattails and Duckweed have shown strong potential as resources for various environmental and economic applications, which will be discussed below.

Cattails

Cattails, also known as Typha species, have been recognized as being suitable biomass crops for wetlands due to their superior productivity (40+ Mt/ha standing crops), pest resistance, adaptability, and chemical composition [58].

Typha latifolia is one of the most widely studied cattail species. It is native throughout the United States, Eurasia, and North Africa. It has been classified as a serious weed in Hungary, a principal weed in Australia, Germany, Italy, Rhodesia, Spain, Tunisia, and a common weed in Argentina, Iran, Kenya, Portugal, and the US [59].

The roots of *Typha latifolia* contain 30% starch, 7.8% crude protein, 1% crude sugar, 0.7% glucose, 0.7% oxalic acid. Aerial portions contain 1.5–3.5% fats, 7–12% crude protein, 38–48% carbohydrates. Based on this composition, as well as the fact that cattails contain roughly 47.6% cellulose and 21.9% lignin, they can therefore be a good feedstock for ethanol production [57, 60]. Furthermore, the pollen, which is used as a medicine and foodstuff, contains 19% crude protein, 17.8% carbohydrates (glucose, fructose, arabinose, rhamnose, xylose) and 1.1% lipids. *Typha latifolia* has also been shown to have potential for use in phytoremediation of constructed wetlands [61].

Duckweed

Duckweed or Lemnaceae is another aquatic plant that has a great potential for biofuel production [62–64]. It is a small, free-floating aquatic plant with fast reproduction, and high resistance to bacteria [65].

The starch content in Duckweed varies within a wide range of 3–75% dry weight, which depends to the species of the individual strains [58]. Recently, researchers at Amity University in India and University of Jena in Germany were able to demonstrate that the absorption of heavy metals and salt (NaCl) in water by the duckweed species Lemna minor lead to an increase in its starch content to approximately 50% of dry mass. This result demonstrates the dual advantage of using Duckweed as a low-cost water purifier and feedstock for bioethanol production [66].

1.7 Conclusion

In this chapter, different categories of biomass for the production of renewable energy, chemicals and biomaterials have been presented. These include woody biomass, agricultural waste, municipal waste, sew-age sludge, algae and aquatic plants. Although woody biomass has traditionally been the major source of energy for cooking and heating in many countries, the rise of waste management directives is promoting the use of waste biomass (i.e. agricultural waste, municipal waste and sewage sludge). Furthermore, algae and aquatic plants represent a new generation of biomass resource for renewable energy and chemicals production, and thus their use offers promising economic and environmental benefits.

References

1. Loppinet-Serani, A., Aymonier, C., Cansell, F.: Current and foreseeable applications of supercritical water for energy and the environment. Chemsuschem **1**(6), 486–503 (2008)
2. World Energy Council: “Biomass,” Energy Resources. https://www.worldenergy.org/data/resources/resource/biomass/. Accessed 24 Mar 2018
3. Basu, P.: Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press, Burlington, MA (2010)
4. Fernandes, S.D., Trautmann, N.M., Streets, D.G., Roden, C.A., Bond, T.C.: Global biofuel use, 1850–2000. Global Biogeochem. Cycles **21**(2) (2007)
5. Biomass (Energy Engineering), What-When-How: In Depth Tutorials and Information. http://what-when-how.com/energy-engineering/biomass-energy-engineering/. Accessed 24 Mar 2018
6. Gallezot, P.: Conversion of biomass to selected chemical products. Chem. Soc. Rev. **41**(4), 1538–1558 (2012)
7. Europäische Kommission (ed.): Being Wise with Waste: The EU’s Approach to Waste Management. Luxembourg: Publ. Off. of the European Union (2010)
8. Knoef H.: Handbook Biomass Gasification. BTG Biomass Technology Group (2012)
9. IEO, International Energy Outlook. Washington DC; Report No.: DOE/EIA-0484 (2013)
10. Evans, L., Okamura, S., Poll, J., Barker, N.: Evaluation of Opportunities for Converting Indigenous UK wastes to Fuels and Energy. AEA/ED45551/Issue 1 (2009)
11. Waste Management World: The Biowaste Directive, Recycling, 01-Jan-2010. https://waste-management-world.com/a/the-biowaste-directive. Accessed 24 Mar 2018
12. Burnley, S., Phillips, R., Coleman, T., Rampling, T.: Energy implications of the thermal recovery of biodegradable municipal waste materials in the United Kingdom. Waste Manag. **31**(9–10), 1949–1959 (2011)
13. Alakangas, E.: European standards for fuel specification and classes of solid biofuels. In: Grammelis, P. (ed.) Solid Biofuels for Energy. Green Energy and Technology. Springer, London (2011)
14. Forest Stewardship Council (FSC): Strategic Review on the Future of Forest Plantations. Helsinki, Finland, A12-06869 (2012)
15. Carle, J., Holmgren, P.: Wood from planted forests: a global outlook 2005–2030. Food Prod. J. **58**(12), 6–18 (2008)
16. Phyllis 2: Database for Biomass and Waste. Energy Research Centre of the Netherlands. Available: https://phyllis.nl/ (2018)

17. Junginger, M., Van Dam, J., Zarrilli, S., Ali Mohamed, F., Marchal, D., Faaij, A.: Opportunities and barriers for international bioenergy trade. Energy Policy **39**(4), 2028–2042 (2011)
18. FAO Forestry Paper: What Wood Fuels can do to Mitigate Climate Change. FAO Forestry Paper 162, Rome (2010)
19. EN 14961-1: Solid biofuels—Fuel Specifications and Classes - Part 1: General Requirements (2010)
20. EN 15359,: Solid Recovered Fuels—Specifications and Classes (2011)
21. WRAP and BSI: PAS 111: Specification for the Requirements and Test Methods for Processing Waste Wood. Available: http://drafts.bsigroup.com/. Accessed Jan 2011
22. European Commission: Waste Generated and Treated in Europe. In: Luxembourg: Office for Official Publications of the European Communities, Available: https://ec.europa.eu/eurostat/documents/3217494/5646057/KS-55-03-471-FR.PDF (2003)
23. Williams, P.T.: Waste Treatment and Disposal, 2nd edn. Wiley Ltd., USA (2005)
24. Smil, V.: Crop residues: agriculture's largest harvest. Bioscience **49**(4), 299–308 (1999)
25. International Atomic Energy Agency (IAEA): Management of Crop Residues for Sustainable Crop Production, Vienna, IAEA Techdoc-1354 (2003)
26. Krupnik, T.J., Six, J., Ladha, J.K., Paine, M.J., van Kessel, C.: An assessment of fertilizer nitrogen recovery efficiency by grain crops across scales. In: Mosier, A.R., Syers, K.J., Freney J.R., (eds.) Agriculture and the Nitrogen Cycle, The Scientific Committee Problems of the Environment. Island Press, Covelo, California, USA (2004)
27. Agele, S.O., Adeyemo, A.J., Famuwagun, I.B.: Agricultural wastes and mineral fertilizer on soil and plant nutrient status, growth and yield of tomato. Arch. Agron. Soil Sci. **57**(1), 91–104 (2011)
28. Great Britain, Department of the Environment: Waste Management Planning: Principles and Practice: A Guide on Best Practice for Waste Regulators. H.M.S.O., London (1995)
29. Lam, J., ter Heegde, F.: Domestic Biogas Compact Course: Technology and Mass-Dissemination Experiences from Asia. University of Oldenburg (2011)
30. Kelleher, B.P., Leahy, J.J., Henihan, A.M., O'Dwyer, T.F., Sutton, D., Leahy, M.J.: Advances in poultry litter disposal technology—a review. Bioresour. Technol. **83**(1), 27–36 (2002)
31. European Commission, "Eurostat: Guidance on Municipal Waste Data Collection (2017)
32. European Environment Agency (EEA): Managing Municipal Solid Waste—A Review of Achievements in 32 European countries. European Environment Agency (2013)
33. Branchini, L.: Chapter 2: Municipal Waste Overview. In Waste-to-Energy. Springer International Publishing, Switzerland (2015)
34. US. EPA: Municipal Solid Waste. https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/. Accessed 23 Nov 2017
35. Lisa, D., Anders, L.: Methods for household waste composition studies. Waste Manag. **28**, 1100–1112 (2008)
36. Hoornweg, D., Bhada-Tata, P.: What a waste—a global review of solid waste management. In: Urban development Series Knowledge Papers. The World Bank (2012)
37. OECD.: List of OECD Member countries—Ratification of the Convention on the OECD. Available http://www.oecd.org/about/membersandpartners/list-oecd-member-countries.htm. Accessed 23 Nov 2017
38. Cheng, H., Hu, Y.: Municipal solid waste (MSW) as a renewable source of energy: current and future practices in China. Bioresour. Technol. **101**(11), 3816–3824 (2010)
39. EPA, United States Environmental Protection Agency: Advancing Sustainable Materials Management: 2014 Fact Sheet. United States Environmental Protection Agency (2016)
40. Agence de l'environnement et de la maîtrise de l'énergie (ADEME): Déchet (2014)
41. Burnley, S.J.: A review of municipal solid waste composition in the United Kingdom. Waste Manag. **27**(10), 1274–1285 (2007)
42. Yuan, X., et al.: Effect of pretreatment by a microbial consortium on methane production of waste paper and cardboard. Bioresour. Technol. **118**, 281–288 (2012)

43. Bridgwater, E., Quested, T.: Synthesis of Food Waste Compositional Data 2012. WRAP. Available: http://www.wrap.org.uk/sites/files/wrap/hhfdw-synthesis-food-waste-composition-data.pdf (2013)
44. Esteves, S., Devlin, D.: Food Waste Chemical Analysis. WRAP. Available: http://www.wrapcymru.org.uk/sites/files/wrap/Technical_report_food_waste_characterisation_Wales_2009x2.9086.pdf (2010)
45. Tchobanoglouss, G., Burton, F.L., Stensel, H.D.: Wastewater Engineering. Treatment and Reuse, 4th edn. McGrawHill, New York (2003)
46. Turovskiy, I.S., Mathai, P.K.: Wastewater Sludge Processing. Wiley, Hoboken (USA) (2006)
47. Foladori, P.: Sludge Reduction Technologies in Wastewater Treatment Plants. IWA Publishing, London (UK) (2010)
48. Yang, G., Zhang, G., Wang, H.: Current state of sludge production, management, treatment and disposal in China. Water Res. **78**, 60–73 (2015)
49. Kelessidis, A., Stasinakis, A.S.: Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Manag. **32**(6), 1186–1195 (2012)
50. EPA: Biosolids Generation, Use and Disposal in the United States. EPA530-R-99–009 (1999)
51. Seiple, T.E., Coleman, A.M., Skaggs, R.L.: Municipal wastewater sludge as a sustainable bioresource in the United States. J. Environ. Manag. **197**, 673–680 (2017)
52. Ericksson, J.: Concentrations of 61 Trace Elements in Sewage Sludge, Farmyard Manure, Mineral Fertiliser, Precipitation and in Oil and Crops. Swedish Environmental Protection Agency, Report 5159 (2001)
53. Kacprzak, M., et al.: Sewage sludge disposal strategies for sustainable development. Environ. Res. **156**, 39–46 (2017)
54. Rideau Valley Conservation Authority: Algae and Aquatic Plant: Educational Manual. Available: http://www.southfrontenac.net/en/town-hall/resources/Algae-Manual-Concise-Final.pdf (2016)
55. Demirbas, A., Fatih Demirbas, M.: Importance of algae oil as a source of biodiesel. Energy Convers. Manag. **52**(1), 163–170 (2011)
56. Raymond, L.P.: Aquatic Biomass as a Source of Fuels and Chemicals. SERI/TP-231-1699, 7146949 (1983)
57. Acosta, M.J.: Advances in Energy Research. Nova Science Publication, New York (2012)
58. Pratt, D.C., Dubbe, D.R., Garver, E.G., Johnson, W.D.: Cattail (*Typha* spp.) Biomass Production: Stand management and sustainable yields. Final report (1988)
59. Holm, L.G., Pancho, J.V., Herberger, J.P., Plucknett, D.L.: A Geographical Atlas of World Weeds. Wiley, New York (1979)
60. Küçük, M.M., Demir, H., Genel, Y.: Supercritical fluid extraction of reed (*Thypa*). Energy Sources **27**(5), 445–450 (2005)
61. Succuro, J.S.: The Effectiveness of using *Typha latifolia* (Broadleaf Cattail) for Photoremediation of Increased levels of Lead-Contamination in Soil. Humboldt State University (2010)
62. Cui, W., Cheng, J.J.: Growing duckweed for biofuel production: a review. Plant Biol. **17**, 16–23 (2015)
63. Xu, J., Zhao, H., Stomp, A.M., Cheng, J.J.: The production of duckweed as a source of biofuels. Biofuels **3**(5), 589–601 (2012)
64. Su, H., et al.: Use of duckweed (*Landoltia punctata*) as a fermentation substrate for the production of higher alcohols as biofuels. Energy Fuels **28**(5), 3206–3216 (2014)
65. Landolt, E.: Extreme adaptation in the angiospermous hydrophytes. In: Anatomy of the Lemnaceae (Duckweeds). Borntraeger, Berlin (1998)
66. Sree, K.S., Appenroth, K.J., Institute, A.: Increase of starch accumulation in the duckweed Lemna minor under abiotic stress. Lbanian J. Agric. Sci. 11–14 (2014)