

1 **Organic Matter Database (OMD): Consolidating global residue data from**
2 **agriculture, fisheries, forestry and related industries.**

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15 **Abstract**

16 Agricultural, fisheries, forestry and agro-processing activities produce large quantities of residues,
17 by-products and waste materials every year. [Inappropriate disposal and inefficient use](#) of these
18 resources contributes to greenhouse gas emissions and non-point pollution, imposing significant
19 environmental and economic burdens to society. Since many nations do not keep statistics of these
20 materials, it has not been possible to accurately quantify the amounts produced, [their competing](#)
21 [uses](#) and [the amount](#) potentially available for recycling. Therefore, the objectives of the present
22 work were to provide: (1) definitions, typologies and methods to aid consistent classification,
23 estimation and reporting of the various residues and by-products; (2) a global organic matter
24 database (OMD) of residues and by-products from agriculture, fisheries, forestry and related
25 industries; and (3) [regional and global](#) estimates of residues and by-products potentially available
26 for use in a circular bio-economy. To the best of our knowledge, the OMD is the first of its kind
27 consolidating quantities and nutrient concentrations of residues and by-products from agriculture,
28 fisheries, forestry and allied industries globally (available at:
29 <https://doi.org/10.5281/zenodo.10450921>). The OMD and its associated products will be
30 continuously updated as new production data are published in FAOSTAT [and improved methods](#)
31 [become available](#), ~~and this~~ [This](#) information is expected to contribute to evidence-based policies
32 and actions in support of sustainable utilization and the transition towards a circular economy. [The](#)
33 [database could be used for a variety of purposes including estimation of residue availability for soil](#)
34 [amendment, livestock feed, bioenergy and other industrial applications, and assessment of](#)
35 [environmental impacts of residue management practices such as soil application and burning](#). The
36 estimates in OMD are available only at the national level. Due to the lack of uniform methodology
37 and data across countries, it was difficult to accurately estimate the quantities of all agricultural,
38 fisheries and forestry residue and by-products. Therefore, we strongly recommend investment in the
39 inventory of agricultural, fisheries and forestry residues, by-products and wastes [at the national and](#)
40 [sub-national levels](#) for use in a circular bio-economy.

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Keywords: Agro-processing; anaerobic digestate; biochar; bioeconomy; compost; manure

1. Introduction

Agricultural, fisheries, forestry and agro-processing activities produce large quantities of residues, by-products and waste materials every year (Gontard et al., 2018; Lopes and Ligabue-Braun, 2021; Millati et al., 2019). [Some of these residues are already being used in a variety of effective ways, such as animal feed and bioenergy feedstock. However, a](#) large proportion of the residues and by-products is either burnt or inappropriately disposed off, without further use (Domingues et al., 2017; FAO, 2022a; Venkatramanan et al., 2021). [This has been widely documented to cause environmental pollution and spread of diseases. For example, manure produced in large-scale dairy, poultry and pig farms continue to cause non-point pollution where disposal is not well-regulated \(Marin et al., 2023; Wang et al., 2017\). Similarly, slaughterhouse residues and agro-processing wastes are often disposed of in open dumps and landfills, where they become a significant source of greenhouse gas \(GHG\) emissions \(Mozhiarasi and Natarajan, 2022\). Some of the wastes from slaughterhouses and agro-processing plants is discharged as effluents into water bodies \(Al-Gheethi et al., 2021\).](#) The burning of crop residues is a major contributor to dangerously high levels of air pollution and emission of greenhouse gases (FAO, 2022a; Oanh et al., 2018; Venkatramanan et al., 2021). In 2019 alone, around 458 million tonnes of crop residues were burnt globally resulting in 1238 kilo tonnes of methane (CH₄) and 32 kilo tonnes of nitrous oxide (N₂O) emissions (FAO, 2022a). Burning agricultural residue also results in substantial losses of nutrients in the residue. For example, burning crop residues results in nearly complete loss of the organic carbon and nitrogen, and loss of 25% of the phosphorus, 20% of the potassium and 5–60% of the sulphur (Dobermann and Fairhurst, 2002). In addition to causing air pollution and respiratory ailments in human, burning also removes opportunities for adding value to crop residues (Lin and Begho, 2022; Oanh et al., 2018; Venkatramanan et al., 2021). [Indeed, the inefficient use of agricultural residues and wastes imposes significant environmental and economic burdens to society \(Gontard et al., 2018\).](#)

68 [Conversely, a significant portion of these residues could enter a circular bio-economy, and their](#)
69 [efficient use can ensure achievement of sustainability goals, through reduction of GHG emissions](#)
70 [and non-point pollution.](#)

71 [Agricultural residues are used in many different ways including soil amendment, for animal](#)
72 [feed and bedding, bioenergy generation, as fuel in industrial and domestic set-ups, mushroom](#)
73 [production, industrial applications such as textiles, natural fibres, polymers, biosorbents and](#)
74 [reinforcement material in composites \(Siqueira et al., 2022; Smerald et al., 2023; Zhao et al., 2024;](#)
75 [see also discussion under sections 4.1–4.4\). A growing body of evidence suggests that currently](#)
76 [unused](#) residues could in principle be [better-more effectively](#) managed to increase soil fertility and
77 productivity, and to mitigate greenhouse gas emissions (Lu et al., 2014; Liu et al., 2015).

78 Over the years, agriculture has increasingly depended on synthetic fertilizers to meet crop
79 nutrient demands. The increased fertilizer use and inefficient fertilizer management practices have
80 led to large nutrient losses to the environment in some regions (FAO, 2022b; Singh and Craswell,
81 2021). On the other hand, farmers in low-income countries have limited access to fertilizer inputs,
82 and this has led to depletion of native soil nutrient stocks from croplands. Access to fertilizers has
83 been further limited by the recent war by Russia on Ukraine, which disrupted a large portion of the
84 global fertilizers supply. The resultant increases in prices are likely to constrain fertilizer use by
85 farmers into the foreseeable future (FAO, 2022c; Behnassi and El Haiba, 2022). In 2020, the
86 production and use of synthetic fertilizers resulted in GHG emissions of 1.0 Gt CO₂ equivalent, of
87 which 62% (or 0.63 Gt CO₂) is emitted when nitrogen fertilizers are used on croplands (FAO,
88 2022d; Tubiello et al., 2022).

89 A growing body of evidence from meta-analyses suggests that the combined use of organic
90 inputs and inorganic fertilizers can increase fertilizer use efficiency (Ba et al., 2022; Chivenge et al.,
91 2011; Sileshi et al., 2019; Wang et al., 2020; Zhang et al., 2020; Melo et al., 2022). There is also a
92 growing consensus that judicious use of agricultural residues can partially substitute for inorganic
93 fertilizers (Fan et al., 2021; Huang et al. 2013; Zhang et al., 2020) and thereby contribute to

94 enhancing the sustainability of food production by reducing costs and carbon footprints while
95 reducing pollution caused by nitrate leaching (Zhang et al., 2020). The savings resulting from
96 recycling agricultural residues and wastes can also be an important contribution to national and
97 local economies. Recycling of organic residues, by-products and wastes can also address waste
98 management problems and reduce GHG emissions from residues and wastes (Andrews et al., 2021;
99 FAO, 2022a).

100 Yet, the potential contributions of agricultural, fisheries and forestry residues and by-products
101 to soil health improvement and carbon management has not been estimated fully. This is largely due
102 to a lack of country statistics on the production of residues and by-products from agriculture,
103 fisheries and forestry, which makes it difficult to accurately quantify the amounts produced and
104 available for recycling. The designation of residues as a resource, by-product or waste may also not
105 always align with how the material is subsequently managed or its potential utility as a soil
106 amendment. For example, livestock manure may be classified as a waste in some jurisdictions but
107 not in others, whether or not it is subsequently used as an organic fertilizer. Importantly, a clear
108 typology of residues and by-products also does not exist in many regions. This hinders the
109 systematic documentation and reporting of the different categories of organic resources.
110 Information is also scant on the quality of most of the residues produced. The quality of organic
111 resource varies with the plant species, plant parts and their maturity level (Palm et al., 2001; Cobo
112 et al., 2002), and determination of the quality attributes using traditional laboratory methods is both
113 timely and costly (Shepherd et al., 2003). Despite these challenges, Palm et al. (2001) published an
114 organic resource database containing data on plant species and plant part, resource quality,
115 decomposition rates, N release rates, digestibility indices and site characteristics. Rapid plant
116 nutrient analysis based on spectroscopic methods have been developed (Shepherd et al., 2003), and
117 complemented with methods assessing functional differences (e.g., carbon and nitrogen release
118 rates, digestibility) (Vanlauwe et al., 2005). Additional efforts to make this organic resource data
119 useful included a decision support system for [testing the four different management different](#)

120 categories of organic resources [as determined by their nitrogen, lignin, and polyphenol contents](#)
121 (Palm et al., 2001; Vanlauwe et al., 2005). A related effort is the Phyllis database developed by the
122 Energy Research Centre of the Netherlands (ECN, 2018) primarily focussing on biomass properties
123 that are relevant to bioenergy and biochar production. Data on primary crop and animal products are
124 available through FAOSTAT, but equivalent data for quantities of residues are not available
125 (Ludemann et al., 2023; Woolf, 2020).

126 In 2020 the Food and Agriculture Organization (FAO) of the United Nations commissioned a
127 scoping study to assess the state of organic resource databases in the agriculture sector and related
128 industries (Woolf, 2020). The study arrived at the following conclusions: (1) large uncertainties
129 exists in the annual production of crop residues; (2) the fate and use of residues and wastes is poorly
130 quantified in many regions of the world; (3) existing decision tools and classification schemes for
131 residue biomass are not well suited for allocating resources amongst a comprehensive portfolio; (4)
132 data on residue biomass composition and properties are diffuse, have large gaps, and rarely relate
133 composition to production conditions; and (5) paucity of data on residue biomass production,
134 composition and fate is a critical constraint on improving resource-use efficiency (Woolf, 2020).
135 Further, the study recommended the development of a global biomass resource database to support
136 sustainable development goals. Therefore, a global database providing [biomass](#) estimates of the
137 different residues and by-products is urgently needed for practitioners and policy-makers to quickly
138 refer to when making decisions. Accordingly, the objectives of the present work were to provide:
139 (1) definitions, typologies and methods to aid consistent classification, estimation and reporting of
140 the various residues and by-products; (2) a global organic matter database of residues and by-
141 products from agriculture, fisheries, forestry and related industries; and (3) [regional and global](#)
142 estimates of residues and by-products potentially available for use in a circular bio-economy.
143 Wherever possible, this work also tried to highlight the competing uses of the various residues and
144 the challenges and opportunities for their use as soil amendments. [The database could be used for a](#)
145 [variety of purposes including estimation of availability of residues for livestock feed, soil](#)

146 [amendment, bioenergy production, industrial applications, and assessment of environmental](#)
147 [impacts \(e.g., pollution, greenhouse gas emissions, nutrient flows\) of residue management practices](#)
148 [\(e.g., residue retention, burning, and disposal\).](#)

149

150 **2. Methods**

151 To guide development of the OMD, a review of the literature was performed. This was aimed at
152 identifying the various categories and a typology (systematic classification) of organic residues and
153 by-products, their competing uses and the challenges and opportunities for their use as soil
154 amendments. The review also aimed at identifying industry’s best-practices and conversion factors
155 for estimating agricultural, fisheries and forestry residues and agro-processing by-products.

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157 **2.1. Data used for creating the OMD**

158 The OMD was designed to provide data on both quantity and quality of residues and by-products
159 (Sileshi et al., 2024 available at: <https://doi.org/10.5281/zenodo.10450921>). Residue datasets were
160 estimated from the FAOSTAT and FishStatJ databases. FAOSTAT provides free access to
161 historical data on food, agriculture, forestry, trade, and land use for over 200 countries and
162 territories. Data on production of primary crop and animal products were extracted from
163 FAOSTAT’s Crop and Livestock Products database (<https://www.fao.org/faostat/en/#data/QCL>),
164 while data on forestry residues came from FAOSTAT’s Forestry Production and Trade database
165 (<https://www.fao.org/faostat/en/#data/FO>) (FAO, 2023). In the case of capture fisheries and
166 aquaculture, production **quantity** (in tonnes live weight) came from FAO’s FishStatJ statistical
167 software (<https://www.fao.org/fishery/static/FishStatJ>) for the periods 2015–2019 for selected
168 species in each country/territory. [In all cases, production refers to the total quantity produced per](#)
169 [country in a given year.](#)

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Not only the quantity, but also the quality of residues, is important for their use in soil
171 amendment. Therefore, a supplementary database was created consolidating data on the nutrient
172 concentrations of various residues to complement the OMD. The concentrations of carbon,

173 macronutrients (nitrogen, phosphorus, potassium), micronutrients (sulphur, calcium, magnesium),
 174 lignin, polyphenols and ratios for crop residues and manure were compiled from existing databases
 175 (e.g., Cornell Substrate Composition Table, FAOSTAT, Phyllis database), International Panel on
 176 Climate Change guidelines (IPCC) default values (IPCC, 2019) and the scientific literature (e.g.,
 177 Ludemann et al., 2023 on crop residues, and Shen et al., 2015; Sileshi et al., 2017 on manure).
 178 Wherever available, the range of values (minimum and maximum) available in OMD and IPCC
 179 default values are summarized in Table 1. All values were reported on dry matter basis. The
 180 moisture contents of most residues have not been reported in the original publications and therefore
 181 values should be used with caution.

182

183 **Table 1.** Range of values (minimum and maximum) reported for the carbon, nitrogen (N), phosphorus (P),
 184 potassium (K), calcium (Ca) and magnesium (Mg) concentrations of crop residues and manure (on dry
 185 matter basis). Values were summarized from the OMD supplementary database described above.

Residue	Carbon (%)	Nitrogen (%)	C:N ratio	P (%)	K (%)	Ca (%)	Mg (%)
Barley straw	47	0.9* (0.5-0.7))		0.09-1.03	1.11-1.18		
Coconut shell	53	1.43	37	0.18	0.50	0.36	0.20
Cocoa beans		2.8		0.18	0.62		
Cocoa pod husks		0.75		0.23	1.02		
Groundnut straw	42	1.30	30	0.15-0.20	1.31-2.19	1.97	1.15
Groundnut hull	49	1.2-2.16	28	0.37	1.27	1.96	0.77
Maize stalks	55	0.81-1.26	69	0.15-0.37	1.20-1.61	0.35	0.48
Rice straw	45-61	0.64-1.69	78-88	0.05-0.11	1.16-2.10	0.42-1.2	0.3-0.52
Rice husk (hull)	39-52	0.48-0.70	70-106	0.11-0.46	0.28-1.3	0.21-0.34	0.09-0.40
Rice bran	50-55	2.0-2.4	18-22	3.60-4.47	1.43-2.45	0.13-0.35	1.11-1.78
Sorghum stalks	53	0.7* (0.7-1.4)	73	0.18-0.25	1.50-1.94	0.60	0.62
Soybean straw	51	0.8* (1.73-2.0)	40	0.14-0.19	0.97-1.63	0.18	0.15
Sugarcane bagasse	33-45	0.3-0.5	65.9	0.03	0.1	0.2	
Wheat straw	47-55	0.7* (0.3-1.4)		0.07	0.86-0.92		
Manure – dairy cows	4.3-61	2.9* (0.3-4.0)	16* (1-98.8)	0.01-3.2	0.03-6.1	0.02-3.5	0.01-1.9
Manure – swine	16-47	4.1* (0.9-4.4)	11* (8-26.1)	0.6-1.8	0.9-1.6	0.4-1.4	0.4-0.8
Manure – poultry	11-50	5.1* (0.5-6.8)	10* (6-37)	0.05-3.9	0.0-4.7	0.02-9.4	0.02-4.8
Manure – sheep and goats	15-49	3.3* (0.8-5.1)	11*	0.12-0.80	0.5-1.8	1.1-3.4	0.4-1.6

186 * Represents IPCC default values

187

188 2.2. Definitions and typology

189 The literature reviewed identified many sources of organic input that can be used for soil
 190 amendment. These include crop residues, agro-processing by-products, forestry and logging
 191 industry residues, manure, poultry and meat processing and fisheries and aquaculture by-products.

192 Authors have used the terms ‘residue’, ‘by-product’, ‘co-product’, ‘waste’, when referring to the
193 various organic resources. Therefore, it was necessary to provide clear definitions and typologies
194 (systematic classification) to facilitate their consistent estimation and compilation in the OMD. A
195 clear definition could only be found in relation to an existing EU directive ([European Parliament
and Council, 2008](#); 2008/98/EC), which was adopted herein. Accordingly, a “by-product” is defined
196 as a substance or object whose primary aim is not the production of that item, whereas “waste” is
197 defined as any substance or object which the holder discards, intends to discard, or is required to
198 discard. According to the Directive, an object or substance should be regarded as a by-product only
199 when certain conditions are met as specified under Article 5. In this paper, this norm was followed
200 and the term “by-product” was consistently used to refer to side products originating from the food
201 manufacturing stage. By-products may be products of either primary or secondary processing of
202 crops [and animals](#), which are available at breweries, wineries, milling and refining facilities [or
slaughterhouses and fish processing facilities](#) (Lopes and Ligabue-Braun, 2021). -Wastes were not
203 included in the OMD as they consist of a wide variety of materials that may be required to be
204 disposed of in accordance with local legislation. Crop residues, agro-processing by-products,
205 manure and forestry residues were included in the OMD.
206

208 209 2.2.1. Crop residues

210 Crop residues were defined as plant parts left on the field after harvest including straw of cereals,
211 pods and stems of legumes, tops, stalks, leaves, and shoots of tuber crops, oil crops, sugar crops,
212 and vegetable crops, and pruning and litter of fruit and nut trees.

213 214 2.2.2. Agro-processing by-products

215 Agro-processing by-products were defined as products from the food and agriculture industry
216 (Lopes and Ligabue-Braun, 2021). According to literature reviewed, the main sources of agro-
217 processing by-products are cereal processing, sugar processing, breweries, the beverage industry,

218 oil presses and bioenergy production, slaughterhouse by-products and fish processing by-products,
219 which are further defined below.

220

221 2.2.2.1. *Cereal processing by-products*

222 Cereal processing by-products are defined here as the by-product of rice milling and the multi-stage
223 process of flour production from cereals such as wheat, rice and maize. In the milling process of
224 rice, the husk (hull), which is the outer cover of the grain, is removed. Further milling removes the
225 bran resulting in white rice. Rice husk constitutes about 20% of the dry weight of rice grains (Singh,
226 2018). The bran is part of cereal grain that could be used in a further milling process or as a
227 biorefinery feedstock (Caldeira et al., 2020).

228

229 2.2.2.2. *Sugar industry by-products*

230 The by-products from the sugar industry include bagasse ~~(the fibrous residue remaining after the~~
231 ~~milling of cane stalks)~~, sugar beet pulp, molasses, and filter press mud, which are available at the
232 milling and refining facilities. Bagasse is the fibrous residue remaining after the milling of cane
233 stalks for juice extraction, and it is roughly 27–28% dry weight of the plant biomass (Bezerra and
234 Ragauskas, 2016). The residue to product ratios (RPR) of bagasse was reported to vary from 0.14 to
235 1.16 (Koopmans and Koppejan (1998)).

236

237 2.2.2.3. *Brewery and winery by-products*

238 Spent grain and grape pomace are the main by-product from the brewery and winery industry,
239 respectively. Barley grain is the main raw material for beer, and ~20 kg of wet brewer's spent
240 grains is produced per 100 litres of beer produced (Gonzalez-Garcia et al., 2018). Approximately
241 75% of grapes produced is intended for wine production, out of which 20–30% represents a by-
242 ~~product called~~ grape pomace consisting of the skin, pulp, seeds, and stalks (Antonić et al., 2020).

243

244 *2.2.2.4. Beverage industry by-products*

245 The beverage industry manufactures ready-to-drink products such as fruit juice, cocoa, coffee and
246 tea-based products, soft drinks, energy drinks, milk products, nutritional beverages. The by-
247 products of fruit processing include the peels, skin, rind and seeds. The main by-products of cocoa
248 processing are cocoa pod husk, cocoa bean shells and cocoa mucilage. In the initial stage of cocoa
249 processing, 70–80% of the fruit is discarded and, approximately ten tonnes of shells are generated
250 for each tonne of cocoa (Dutra et al., 2023).

251 In making the coffee beverage, approximately 90% w/w dry matter of the coffee cherry is
252 discarded in the form of husks, parchments, mucilage, silver skin and spent coffee grounds
253 (Iriundo-DeHond et al., 2020). On wet weight basis, in 100 kg of mature coffee cherries, 39 kg
254 corresponds to the skin and pulp and 22 kg of mucilage and about 39 kg of parchment is generated
255 (Iriundo-DeHond et al., 2020).

256

257 *2.2.2.5. Oil processing by-products*

258 The main oil crops include oil palm, coconut, groundnut, soybeans and olives. By-products from
259 palm oil mills include empty fruit bunches (EFB), palm oil mill effluent, decanter cake, seed shells
260 and the fibre from the mesocarp. A hectare of oil palm produces 10–35 tonnes of fresh fruit bunch
261 (FFB) per year on wet weight basis. EFB, fiber, shells and decanter cake account for 30, 6, 3 and
262 29% of the fresh fruit bunch (FFB), respectively (Embrandiri et al., 2012). EFB is the residue left
263 after the processing of fresh fruit bunch at the mill. Palm press fibre (PPF) or mesocarp fibre is
264 produced after pressing fruit or mesocarp to obtain oil. On average, for every tonne of FFB
265 processed, 120 kg of fibre is produced on wet-weight basis (Embrandiri et al., 2012). Palm kernel
266 shell (PKS) is difficult to decompose and it has been used as mulch. Decanter cake is another waste
267 product used as either fertilizer or animal food. Palm oil mill effluent is the outcome of oil
268 extraction, washing and cleaning processes in the mills. On wet weight basis, about 3 tonnes of oil
269 mill effluent is produced for every tonne of oil extracted in an oil mill.

270 Coconuts consists of husks (33–35%), shell (12–15%) and copra (28–30%) on wet weight
271 basis. According to Onwudike (1996) about 2,220 kg of dry husks and 1,040 kg of dry shells become
272 available per hectare per year. Lim (1986) gives figures of 5,280 kg of dry husks and 2,510 kg of
273 dry shells per ha per year in large-scale estates. Copra production ranges from 0.5–1 tonnes per ha
274 per year with traditional harvesting on small holdings to 3–9 tonnes per ha for improved clonal
275 varieties and intensive management (Lim, 1986).

276 The processing of groundnut oil produces a large portion of peanut meal as a by-product, and
277 skins and hulls. On wet-weight basis, a 1000 kg of peanuts can generate about 500–700 kg of
278 peanut meal depending on the procedure of oil extraction (Zhao et al, 2012). An estimated 35–45 g
279 of skin and 230–300 g of hulls are generated per kg of shelled groundnut kernel (Zhao et al, 2012).
280 Soybean curd residue is the main by-product of soybean products, and about 1.1 kg of fresh curd
281 residue is produced from every kilogram of soybeans processed into soymilk or tofu (Khare et al.,
282 1995). The manufacturing process of the olive oil yields a semi-solid waste called olive cake (30%)
283 and aqueous liquor (50%). About 10 g of olive cake is produced per kilogram of virgin olive oil
284 processed (Masella et al., 2014).

285

286 2.2.2.6. *Bioenergy by-products*

287 The main routes in the production of bioenergy are pyrolysis and gasification and anaerobic
288 digestion (Hamelin et al., 2019; Masoumi et al., 2021). The main bioenergy by-products with
289 potential use in soil amendment include (1) biochar from thermochemical conversion with pyrolysis
290 producing bio-oil and gasification producing syngas as the main product; (2) hydrochar from
291 hydrothermal liquefaction with bio-oil as the main product; (3) digestate from anaerobic digestion
292 with biogas as the main product; and (4) molasses from lignocellulosic ethanol production with
293 bioethanol as the main product (Hamelin et al., 2019; Karan and Hamelin, 2021; Masoumi et al.,
294 2021). Conversion of agricultural residues and by-products into biochar provides an option for
295 better waste management and reducing the residue volume to be applied (Alkharabsheh et al.,

296 2021). Biological methods such as digestion and composting do not reliably get rid of contaminants
297 such as antibiotics, heavy metals and pathogens from agricultural and fisheries residues. Processing
298 these materials into biochar, however, can destroy pathogens and pollutants such as hormones and
299 antibiotics given the high temperatures during pyrolysis. In addition, biochar has been [reported](#) to
300 control plant diseases (de Medeiros et al., 2021; Poveda et al., 2021).

301 Due to the need for drying the feedstock for pyrolysis that can be energy-intensive and costly
302 for very wet feedstock, hydrothermal carbonization is considered as an alternative to pyrolysis.
303 Hydrothermal carbonization is carried out at relatively lower temperatures of 80-240 °C, under
304 subcritical water pressure (Padhye et al., 2022). The solid output of this process is called hydrochar
305 (Masoumi et al., 2021; Padhye et al., 2022).

306 Biogas production involves anaerobic digestion of organic wastes to produce methane (Akbar
307 et al., 2021; Ma et al., 2022). This process produces large quantities of digestate that can be used as
308 soil amendment. Since anaerobic digestion deactivates pathogens (Ma et al., 2022), it is also safer
309 than direct application biowaste. Due to increasing numbers of livestock feeding operations and the
310 consequent increase in the number of large-scale biogas plants, huge quantities of digestate are
311 produced in some regions. Digestate probably has more than 80% moisture, whereas hydrochar can
312 have 20-50% moisture content.

313

314 2.2.2.7. *Slaughterhouse by-products*

315 [Slaughterhouse by-products](#) These consist of poultry and meat processing by-products. [The inedible](#)
316 [parts of slaughtered animals vary with the species, ranging from 22% for turkey, 37% for broilers,](#)
317 [38-40% for pigs, 47% for sheep and goats, and 49% for cattle;](#) (Mozhiarasi and Natarajan, 2022).

318

319 2.2.2.8. *Fish processing by-products*

320 Fish processing by-products include the trimmings of fish either in aquaculture or capture fisheries,
321 for example heads, frames, skin and tails. These materials may constitute up to 70% of fish and

322 shellfish after processing. Depending on the market, some species are not processed at all, while
323 others, especially larger fish, are often extensively transformed to fillets or parts of fillets. Fish fillet
324 yield is species-dependent and is often in the range of 30–50% of the fish on wet weight basis.

325

326 2.2.3. Livestock manure

327 Livestock manure is defined here as the excreta of domestic animals (e.g., poultry, cows, sheep,
328 horses, rabbits, etc.) including the plant material used as bedding for animals. Two major categories
329 of manure source are recognized by the IPCC: manure management systems and manure left on
330 pasture. Manure left on pasture is difficult to collect and therefore largely unavailable for use as soil
331 amendment. In management systems, manure may be found in liquid (liquid or slurry) or solid form
332 in cattle, pig and poultry farms. In such systems, cattle produce large quantities of manure, with
333 dairy cows producing 62 kg per day or about 10% of the weight of an average cow on wet weight
334 basis (EnviroStats, 2008). Feedlot cattle can generate manure about 5–6% of their body weight each
335 day or a dry mass of roughly 5.5 kg per animal per day (Font-Palma, 2019). Full-grown milking
336 cows can produce 7–8% of their body weight as manure per day or roughly 7.3 kg dry mass per
337 animal per day (Font-Palma, 2019). Bulls, beef cows, steers, heifers and calves produce 42, 37, 26,
338 24 and 12 kg manure per animal per day, respectively (EnviroStats, 2008). Different categories of
339 pigs produce 1–4 kg of manure per day, while poultry species produce less than 1 kg of manure per
340 day.

341

342 2.2.4. Forestry residues

343 Forestry residues can be divided into primary and secondary residues (Karan and Hamelin, 2020).
344 Primary residues are defined as residues that are left after logging operations (e.g., branches,
345 stumps, treetops, bark, etc.), whereas secondary residues are by-products and co-products of
346 industrial wood-processing operations (Karan and Hamelin, 2020). Primary residues were excluded
347 from the OMD because they are often unavailable for agricultural use. Here, only wood residues

348 were included. The FAOSTAT definition of wood residues covers wood that has passed through
349 some form of processing but which also constitutes the raw material of a further process such as for
350 particle board, fibreboard or energy purposes (FAO, 2022e). This excludes wood chips, made either
351 directly in the forest from roundwood or made in the wood processing industry (i.e., already
352 counted as pulpwood or wood chips and particles), and agglomerated products such as logs,
353 briquettes, pellets or similar forms as well as post-consumer wood.

354

355 **2.3. Estimating the quantities produced**

356 Due to the lack of databases on agricultural residues and by-products, practitioners often use residue
357 to product ratios (RPR) to estimate residue biomass from data on production of primary products
358 obtained from local statistics or global databases such as FAOSTAT and EUROSTAT (e.g.,
359 Bentsen et al., 2014; Bedoić et al., 2019; Karan and Hamelin, 2021; Ronzon and Piotrowski, 2017).
360 The estimation is sometimes done assuming a mathematical relationship (e.g., linear, logarithmic,
361 hyperbolic or exponential function) between the primary crop yield and the residue yield (Bentsen
362 et al., 2014; Ronzon and Piotrowski, 2017). The disadvantage of the RPR is that it is constant over
363 time and space for a given crop, whereas methods based on mathematical functions can be more
364 flexible. In this work, the estimation of residues and by-products generally followed IPCC
365 guidelines (IPCC, 2019) and the FAO guidelines in the Bioenergy and Food Security Rapid
366 Appraisal user manual for crop and livestock residues (FAO, 2014). In the case of crop residues, the
367 IPCC provides two alternative methods for estimation of the aboveground crop residue yield
368 ($AG_{DM(T)}$) in $kg\ ha^{-1}$ on dry mass basis. The first method involves multiplying the harvested crop
369 yield with the ratio of aboveground dry matter ($R_{AG(T)}$) provided in Table 11.A of IPCC (2019). The
370 second method involves estimation of residue yields from crop yield using linear equations in Table
371 11.2 (IPCC, 2019). For any given given crop (T), the two methods are expressed as follows
372 following the exact IPCC notations:

373 First method: $AG_{DM(T)} = Crop_{(T)} \times R_{AG(T)}$

374 Second method: $AG_{DM(T)} = Crop_{(T)} \times Slope_{(T)} + Intercept_{(T)}$

375 The first method always yields a constant harvest index, [and](#) most of the times [it yields](#) larger than
376 the typical values reported in the literature (e.g., Ludemann et al., 2023). For example, the IPCC
377 default values of $R_{AG(T)} = 1$ and 1.2 for maize and barley yield harvest indices of 0.50 and 0.47,
378 while the typical values are less than 0.47 and 0.41, respectively. As a result, the first method
379 systematically underestimates residue production relative to the second method. The advantage of
380 the second method is that it yields a more realistic harvest index commensurate with the grain yield
381 achieved in a particular country and year. Therefore, the second method was chosen for estimating
382 $AG_{DM(T)}$ from $Crop_{(T)}$ in FAOSTAT for the period 2015-2020. Then, the total annual above-ground
383 residue production ($AGR_{(T)}$) was calculated for each crop (T) by multiplying $AG_{DM(T)}$ by the
384 harvested area available in FAOSTAT per country and year for maize, wheat, rice, barley, soybean
385 and groundnut. The average values of six years (2015–2020) per country were summed across
386 countries to provide annual aboveground residue production estimates ($AGR_{(T)}$) in tonnes on dry
387 matter basis) for each region. [Then these values were added to produce a global estimate of total](#)
388 [residue production. The uncertainty around each estimate was expressed with 95% confidence](#)
389 [limits \(CLs\). It is not possible to generate estimates such as the standard errors or 95% confidence](#)
390 [limits of the sum of quantities using conventional statistical methods. Therefore, the 95% CLs were](#)
391 [estimated using bias-corrected bootstrapping, a non-parametric method which involves random](#)
392 [resampling of the sample totals \(sum\) with replacement.](#)

393

394 **Table 2.** The IPCC equations used for estimation of above-ground crop residue yield ($AG_{DM(T)}$) in tonnes per
 395 ha) from grain yield ($Crop_{(T)}$ in tonnes per ha) from FAOSTAT, and IPCC default values for dry matter
 396 fraction of harvested product and dry matter fraction of aboveground crop residue.

Crop	IPCC equation for $AG_{DM(T)}^{\dagger}$	IPCC default values	
		Dry matter fraction of harvested product, $R_{AG(T)}^{\dagger}$	Dry matter fraction of aboveground crop residue [‡]
Wheat	$0.52+1.51*Crop_{(T)}$	0.89	0.86
Maize	$0.61+1.03*Crop_{(T)}$	0.87	0.82
Oat	$0.89+0.91*Crop_{(T)}$	0.89	0.77
Barley	$0.59+0.98*Crop_{(T)}$	0.89	0.84
Rice	$2.46+0.95*Crop_{(T)}$	0.89	0.87
Millet	$0.14+1.43*Crop_{(T)}$	0.90	0.85
Sorghum	$1.33+0.88*Crop_{(T)}$	0.89	0.85
Rye	$0.88+1.09*Crop_{(T)}$	0.88	0.85
Groundnuts	$1.54+1.07*Crop_{(T)}$	0.94	0.90
Dry beans	$0.68+0.36*Crop_{(T)}$	0.91	--
Soybean	$1.35+0.93*Crop_{(T)}$	0.91	0.85

397 [†]These are all dry matter values at grain moisture contents of 9–13% or dry matter fraction of 0.87–0.91.

398 [‡] Values are from Ludemann et al. (2023).

399

400 Production of agro-processing by-products is often estimated using the RPR and related
 401 coefficients following the FAO guidelines (FAO, 2014). Wherever available, these values defined
 402 as extraction rates, were obtained from FAO’s Technical Conversion Factors for Agricultural
 403 Commodities (FAO, 2009). When not available, average values from the literature were used for
 404 estimating the various by-products from the production data in FAOSTAT. [For example, the](#)
 405 [median value of 0.29 from Koopmans and Koppejan \(1998\) was used to estimate bagasse from](#)
 406 [sugarcane.](#)

407 Poultry processing by-products were estimated from the take-off rate, dressed carcass weight
 408 (% of live weight) and stocks (heads) using the following equation:

409 $Residue = (take-off\ rate/100)*average\ live\ weight*(100-\% \text{ carcass weight})*stocks$

410 For each poultry species (chickens, ducks, geese and turkeys) in each country/territory, the take-off
411 rate (in %), average live weight (kg/animal), and dressed carcass wet weight (in %) were obtained
412 from FAO's Technical Conversion Factors for Agricultural Commodities (FAO, 2009), while
413 stocks (number of animals) were obtained from FAOSTAT Crops and livestock products
414 (<https://www.fao.org/faostat/en/#data/QCL>).

415 Similarly, meat processing by-products were estimated from the take-off rate, dressed carcass
416 weight (% of live weight) and stocks (heads) using the following equation:

417
$$\text{Residue} = (\text{take-off rate}/100) * \text{average live weight} * (100 - \% \text{ carcass weight} - \% \text{ hides/skins} - \% \text{ edible}$$

418
$$\text{offal}) * \text{stocks}$$

419 The dressed carcass weight is the weight of the carcass after removal of hide/skin, head, feet, offal,
420 raw fats, and blood which is often not collected in the course of slaughter. For each species
421 (buffaloes, cattle, sheep, goats, horses, camels and pigs) in each country/territory, the take-off rate
422 (in %), average live weight (kg/animal), and dressed carcass wet weight (in %) were ~~obtained~~
423 ~~available from in~~ FAO's Technical Conversion Factors for Agricultural Commodities. As in the
424 poultry species, stocks were ~~obtained available from in~~ FAOSTAT Crops and livestock products for
425 each country/territory. Carcass weight, ~~edible and non-edible offal~~ was ~~used~~ as defined in FAO's
426 Livestock statistics: Concepts, definitions and classifications (FAO, 2011). According to the
427 definition in FAO (2011), edible offal in most countries include head or head meat, throat bread,
428 thick skirt, tongue, sweet bread, genital organs, brains, lungs, udder, feet, liver, stomach or tripes,
429 tail meat, spleen, blood, heart and diaphragm. -In this calculation, the non-edible portions are
430 assumed to be disposed off in slaughter houses and these were considered as residues. However, in
431 certain circumstances parts such as head, feet, fat and blood can be used in a variety of ways. Since
432 data are not available from slaughter houses on specific uses of non-edible offal, we were unable to
433 establish the alternative uses.

434 Residues from capture fisheries and aquaculture species were estimated using the conversion
435 factors in the Handbook of Fishery Statistical Standards (CWP, 2004) for selected species. In the

436 fisheries industry, the term "conversion factor" is used principally when converting the volume or
437 mass (more commonly referred to as the "weight") of a product at one stage to its volume or mass at
438 another stage in the chain (FAO, 2004). Conversion factors for a particular state of processing vary
439 according to species and state of processing. The state of processing is hierarchical, and may consist
440 of the following categories: (a) gutted, (b) headed and gutted, (c) dressed, (d) fillet (skin on or off),
441 etc. The FAO global inland and marine capture database includes catches for over 2000
442 species/items (including the "not elsewhere included" categories). Since conversion factors are not
443 available for all species, first species were ranked based on the number of countries producing and
444 the total production in 2019. Then the top 6 species were selected for the present analysis because
445 of availability of conversion factors and the large number of countries involved in their production.
446 Among the aquaculture species, rainbow trout (*Oncorhynchus mykiss*) was chosen as it was the
447 topmost grown in aquaculture in 91 countries. In capture fisheries, yellow fin tuna (*Thunnus*
448 *albacares*), skipjack tuna (*Katsuwonus pelamis*), swordfish (*Xiphias gladius*), Bigeye tuna
449 (*Thunnus obesus*) and albacore (*Thunnus alalunga*) were chosen for the analysis. Each of these
450 species were harvested in 96, 90, 83, 79 and 71 countries, respectively. The production quantity was
451 then converted to residues as follows: Value-(Value/CF) where CF is the indicative factors for
452 converting product weight to live weight. The FAO database of capture fisheries production covers
453 only retained catches; data on by-catch (discarded catches) are not included (Garibaldi, 2012). This
454 means that the by-products can be severely underestimated.

455 Manure production (in tonnes/year on dry matter basis) was estimated from manure excretion
456 rate (kg/head/day on dry-weight basis) and stocks (from FAOSTAT) following the FAO guideline
457 for the different animal categories (FAO, 2014). The general formula for manure production is as
458 follows:

$$459 \text{ Manure production (tonnes/year)} = (365 * \text{stocks} * \text{manure excretion rate}) / 1000$$

460 Since there is no global database which provides country-specific data on manure production, the
461 FAO tool uses the IPCC default values (FAO, 2014). For each species, average manure excretion

462 rates were obtained from values compiled from the literature. For the USA, excretion rates were
463 obtained from ASAE Standards D384.1 of the American Society of Agriculture Engineers (ASAE)
464 Manure production and characteristics (2005). Manure production was estimated for different
465 management systems of cattle (non-dairy and dairy) and chicken (broilers and layers) separately
466 because these are always managed as separate enterprises.

467 When compiling forestry residues, primary residues were excluded because of the concerns
468 related to the environmental and economic sustainability of removing them from the forest for soil
469 application on farm-land. Therefore, the analysis focused on wood residues following the FAO
470 definition. Data on production quantity of wood residues (item code 1620) in FAOSTAT
471 (<https://www.fao.org/faostat/en/#data/FO>) were used for compiling the OMD. These are reported in
472 cubic meters solid volume excluding bark on FAOSTAT.

473 A database of all the coefficients and RPR used in the estimation of the various residues and
474 by-products is now available in the OMD.

475

476 **3. Results**

477 **3.1. Crop residues**

478 Maize had the largest global total annual above-ground residue production (~1.28; [CL: 0.43–2.33](#)
479 billion tonnes) followed by wheat (~1.25; [CL: 0.66–1.91](#) billion tonnes) and rice (~1.11; [CL:](#)
480 [0.09–1.93](#) billion tonnes) (Table 3). The estimated quantities of crop residue varied widely by
481 continent and region. For example, the largest total annual production of maize residue was
482 recorded in Northern America including Canada and USA (~0.41 billion tonnes) followed by
483 Eastern Asia (~0.30 billion tonnes) including China, Democratic People’s Republic of Korea, South
484 Korea and Japan; China accounted for over 99% of the residues produced in Eastern Asia. The
485 largest wheat residue production was recorded in Southern Asia (~0.24 billion tonnes) including
486 Afghanistan, Bhutan, India, Iran, Nepal and Pakistan and Sri Lanka, of which over 67% was
487 produced in India. Rice residue production was highest in Southern Asia (~0.38 billion tonnes), of

488 which over 70% was produced in India. The global total annual residue production from soybean
489 was ~0.49 million tonnes, while for groundnuts the corresponding value was ~0.10 billion tonnes
490 (Table 3). The largest soybean residue production was recorded in South America (~0.25 billion
491 tonnes) of which Brazil accounted for 61% of soybean residue production in that region. This was
492 followed by Northern America (~0.16 billion tonnes) of which USA accounted for 94% of soybean
493 residue production in Northern America.

494

496 **Table 3.** Estimated total[†] annual crop residue potentially produced (in 1000 tonnes on dry matter basis) by
 497 selected crops across different regions estimated from FAOSTAT data (see methods).

	<u>Geographic region</u>	Maize	Wheat	Rice	Barley	Soybean	Groundnut
Africa	Eastern Africa	42622	9530	15061	2901	1534	7056
	Middle Africa	11522	30	6405	0	212	5782
	Northern Africa	8534	32724	5817	5676	62	6279
	Southern Africa	14502	2908	8	450	1995	131
	Western Africa	32457	194	44747	2	2614	21973
Americas	Caribbean	929	0	2279	0	0	99
	Central America	37518	5438	1972	1105	710	469
	Northern America	412953	141792	11567	14628	159366	5054
	South America	170584	44654	34221	6342	244685	2824
Asia	Central Asia	2485	42233	1851	5727	411	50
	Eastern Asia	297844	216137	302030	1731	26656	25378
	South-Eastern Asia	53698	227	293393	166	2555	6118
	Southern Asia	49564	244427	383033	6744	26561	16884
	Western Asia	8152	50475	1605	14488	197	393
Oceania	Australia and New Zealand	646	39395	503	12701	50	23
	Melanesia	27	0	21	0	0	11
	Micronesia	0	0	0	0	0	0
Europe	Eastern Europe	86330	238524	1752	45433	13930	1
	Northern Europe	156	47468	0	19172	0	0
	Southern Europe	25701	32708	3613	12573	2617	8
	Western Europe	21935	102338	115	25998	912	0
Total		1278157	1251201	1109994	175835	485065	98533
<u>Lower 95% CL[†]</u>		<u>428190</u>	<u>663830</u>	<u>93059</u>	<u>107947</u>	<u>89264</u>	<u>41188</u>
<u>Upper 95% CL[†]</u>		<u>2328569</u>	<u>1905111</u>	<u>1931334</u>	<u>244998</u>	<u>933898</u>	<u>163731</u>

498 [†] Values represent the lower and upper 95% confidence limits estimated using bootstrapping

499

500 3.2. Agro-processing by-products

501 3.2.1. By-products from processing crops

502 Globally, maize processing yielded the largest quantity of by-products (~ 0.12 ; [CL: 0.04–0.23](#)
 503 billion tonnes) followed by wheat (~ 0.10 ; [CL: 0.05–0.15](#) billion tonnes), rice (~ 0.09 ; [CL: 0.03–0.16](#)
 504 billion tonnes) and barley (~ 0.04 ; [CL: 0.03–0.06](#) billion tonnes) (Table 4). The largest quantity of
 505 maize processing by-products was recorded in Northern America, followed by Eastern Asia and
 506 South America. The largest quantity of wheat processing by-products was recorded in Southern
 507 Asia followed by Eastern Europe and Eastern Asia (Table 4). [The global sugarcane bagasse](#)
 508 [production is estimated at 548.7 million tons per annum \(Table 5\), of which of 44.8 and 23.8% is](#)
 509 [produced in South America and Southern Asia, respectively. Brazil accounts for 89.1% of the](#)

510 [annual bagasse production in South America. Similarly, India accounts for 80.3% of the annual](#)
 511 [bagasse production in Southern Asia.](#)

512 The global annual production of by-products of coffee, cocoa and oil palm processing were
 513 estimated at 20.5, 5.3 and 170.1 million tonnes (Table 4). The largest quantity of coffee-processing
 514 by-products was recorded in South America, with Brazil producing about 6.5 million tonnes
 515 accounting for over 71% of the annual production in South America. This was followed by South-
 516 Eastern Asia, where Viet Nam produced 3.3 million tonnes annually. The largest quantity of by-
 517 products from cocoa was produced in West Africa, where Cote d'Ivoire accounted for over 60% of
 518 the production in that region. Out of the 170.1 million tonnes of global annual oil palm by-products,
 519 Indonesia accounted for over 59% of the total annual global production.

520 **Table 4.** Estimated total annual agro-processing by-products of [different-selected cereal and legume](#) crops
 521 produced (in 1000 tonnes on dry matter basis) across different regions. All values were estimated using
 522 FAOSTAT data (see methods).
 523

	Geographic region	Maize	Wheat	Rice	Barley	Soybeans	Groundnut
Africa	Eastern Africa	3493	727	963	671	63	794
	Middle Africa	789	1	219	0	6	824
	Northern Africa	827	2492	569	1101	4	903
	Southern Africa	1376	227	0	114	95	20
	Western Africa	2568	14	2345	0	92	3227
Americas	Caribbean	68	0	179	0	0	13
	Central America	3415	439	162	269	32	107
	Northern America	41834	11050	1117	3737	9525	1007
	South America	16501	3440	2992	1606	14294	649
Asia	Central Asia	243	2983	134	1214	21	12
	Eastern Asia	28988	17498	27778	434	1292	6338
	South-Eastern Asia	5073	16	23094	39	109	1159
	Southern Asia	4484	18827	29327	1517	960	3007
	Western Asia	809	3860	147	3362	12	82
Europe	Eastern Europe	8380	18618	151	11092	663	0
	Northern Europe	15	3883	0	5097	0	0
	Southern Europe	2565	2576	333	3147	155	2
	Western Europe	2196	8405	10	7032	50	0
Oceania	Australia, New Zealand	64	2890	51	2975	2	6
	Melanesia	2	0	1	0	0	2
	Micronesia	0	0	0	0	0	0
	Polynesia	0	0	0	0	0	0
	Total	123690	97945	89569	43406	27373	18149
	Lower 95% CL[†]	39858	52502	30167	27039	4939	6509
	Upper 95% CL[†]	227872	149319	158790	61570	54359	33070

524 [†] Values represent the lower and upper 95% confidence limits estimated using bootstrapping

525

526 **Table 5.** Estimated total annual [production of](#) agro-processing by-products of ~~different crops~~ [coffee, cocoa,](#)
527 [oil palm and sugarcane](#) produced (in 1000 tonnes on dry matter basis) across different regions. All values
528 were estimated using FAOSTAT data (see methods).

	Geographic region	Sugarcane bagasse	Coffee	Cocoa	Oil palm
Africa	Eastern Africa	9697	2051	58	80
	Middle Africa	1615	206	285	2117
	Northern Africa	6390	0	0	0
	Southern Africa	6676	0	0	0
	Western Africa	3040	292	3295	7241
Americas	Caribbean	7095	110	100	118
	Central America	33000	2244	50	3130
	Northern America	8772	5	0	0
	South America	245883	9145	720	6096
Asia	Central Asia	0	0	0	0
	Eastern Asia	31493	110	100	118
	South-Eastern Asia	53949	2244	50	3130
	Southern Asia	130849	5	0	0
	Western Asia	2	9145	720	6096
Europe	Eastern Europe	0	0	0	0
	Northern Europe	0	0	0	0
	Southern Europe	2	0	0	0
	Western Europe	0	0	0	0
Oceania	Australia, New Zealand	9645	0	0	0
	Melanesia	589	104	43	1293
	Micronesia	0	0	0	0
	Polynesia	0	0	0	0
	Total	548697	20511	5268	170137
	Lower 95% CL[†]	162720	7552	1442	18438
	Upper 95% CL[†]	1059340	35576	9852	384960

529 [†] [Values represent the lower and upper 95% confidence limits estimated using bootstrapping](#)

530

531

532 3.2.2. By-products from slaughterhouses

533 Globally, the largest quantity of residues produced annually was from cattle (16.5 million tonnes)
534 followed by chicken (10.7 million tonnes) and pigs (6.2 million tonnes), but with wide variation
535 among regions (Table [65](#)). The largest quantity of by-products from cattle was recorded in South
536 America (5.31 million tonnes) of which Brazil accounted for 77% of by-products produced in that
537 region. This was followed by Northern America (4.59 million tonnes of which 94% was in USA)
538 and Eastern Asia (0.99 million tonnes of which 84% was produced in China). The total annual
539 production of by-products from [chicken-poultry](#) processing was largest in North America (6.0
540 million tonnes) of which over 99% was produced in the USA. This was followed by East Asia (0.91
541 million tonnes) of which China accounted for over 72% of the production in East Asia.

542

543 **Table 56.** Estimated total annual quantity of slaughterhouse by-products potentially produced (in 1000
 544 tonnes on dry matter basis) across different regions. All values were estimated using FAOSTAT data (see
 545 methods).

Continent	Geographic region	Cattle	Buffalo	Sheep	Goats	Pigs	Chicken	Turkeys
Africa	Eastern Africa	436	-	84	133	80	65	1
	Middle Africa	141		60	2067	17	12	
	Northern Africa	162	33	161		0	158	7
	Southern Africa	125	723	31	8	11	119	0
	Western Africa	306		94	168	31	57	
Americas	Caribbean	51		2	3	24	79	0
	Central America	450		8	5	81	153	1
	Northern America	4591		25	46	1072	6004	51
	South America	5311		42	14	272	864	8
Asia	Central Asia	321		141	12	8	19	
	Eastern Asia	994	48	108	117	2482	906	0
	South-Eastern Asia	206	47	27	41	409	748	0
	Southern Asia	625		181	388	39	574	1
	Western Asia	175	3	175	45	6	202	6
Europe	Eastern Europe	433	1	68	5	327	287	38
	Northern Europe	407		91		303	275	5
	Southern Europe	297	1	66	14	354	14	1
	Western Europe	847		35	4	671	142	28
Oceania	Australia and New Zealand	605		399	35	35	55	3
	Melanesia	2		0	0	9	2	0
	Micronesia					0	0	
	Polynesia	1		0	0	1	0	
Total		16487	855	1797	3104	6231	10735	150
Lower 95% CL[†]		6491	108	1122	630	2306	2925	46
Upper 95% CL[†]		28977	1896	2589	7205	11227	22724	273

546 [†] Values represent the lower and upper 95% confidence limits estimated using bootstrapping

547

548 3.3.3. By-products from fisheries and aquaculture

549 The estimated annual quantity of by-products potentially produced from processing of selected fish species
 550 in aquaculture and capture fisheries are summarized in Table 6. Among the species grown in aquaculture,
 551 the largest quantity of by-products was produced by rainbow trout (over 0.08 million tonnes) across
 552 91 countries (Table 76). The largest proportion was recorded in Southern Asia (predominantly in
 553 Iran and Turkey), followed by South America (mainly in Peru and Chile) and Northern Europe
 554 (mostly in Norway) (Table 76). Among the capture fisheries species, the largest quantity of by-
 555 products was produced from skipjack tuna harvest (0.14 million tonnes) followed by yellowfin tuna
 556 (0.08 million tonnes).

557

558 **Table 76.** Estimated total annual quantity of by-products potentially produced (in tonnes on dry matter
559 basis) by selected fish species in aquaculture and capture fisheries across different regions. All values were
560 estimated using FishStatJ data (see methods).

Continent	Geographic region	Aquaculture	Capture fisheries				
		Rainbow trout	Albacore	Bigeye	Skipjack	Swordfish	Yellowfin
Africa	Eastern Africa	90	100	560	4550	250	3170
	Middle Africa	0	0	70	360	10	190
	Northern Africa	10	40	20	60	370	10
	Southern Africa	340	210	40	0	100	80
	Western Africa	0	40	680	7100	50	2980
Americas	Caribbean	0	30	320	2060	10	1200
	Central America	1110	20	380	2150	120	4580
	Northern America	2970	230	210	3140	230	590
	South America	14150	130	1880	9620	1650	7110
Asia	Central Asia	180	0	0	0	0	0
	Eastern Asia	5110	990	960	5210	260	1670
	South-Eastern Asia	0	710	2560	33290	470	15580
	Southern Asia	14730	0	510	13820	810	13880
	Western Asia	6860	60	0	130	280	4920
Europe	Eastern Europe	6740	30	0	0	0	0
	Northern Europe	13150	240	0	10	10	0
	Southern Europe	6090	300	310	1680	730	770
	Western Europe	5200	100	100	610	10	790
Oceania	Australia and New Zealand	0	170	40	180	160	120
	Melanesia	10	1560	1080	21470	40	12920
	Micronesia	0	250	1830	28450	20	6250
	Polynesia	0	690	240	670	30	540
Total		76740	11790	134560	5610	77350	76740

561
562

563 3.3. Livestock manure

564 Globally, cattle, buffaloes and chicken produced the largest proportion of the potential annual
565 manure produced every year (Table 87). [On dry matter basis](#), [Nonmon](#)-dairy cattle produce an
566 estimated 2.23 billion tonnes [\(CL: 1.32–3.23\)](#), while dairy cattle produce about 0.82 billion tonnes
567 [\(CL: 0.50–1.21\)](#) annually [on dry matter basis](#). The largest quantity of non-dairy cattle manure was
568 produced in South America (where Brazil accounts for 60%) followed by South Asia (where India
569 accounts for 68%). Annual production of dairy cattle manure was largest in South Asia (where India
570 accounts for 68%). The largest annual manure production by buffaloes occurs in East Asia (China
571 accounts for 99%) and South Asia (India accounts for 70%). The largest quantity of broiler chicken
572 manure was recorded in South-Eastern Asia, where Indonesia accounts for 76% of broiler chicken

573 manure in that region. The next largest production was recorded in South Asia where Pakistan and
 574 Iran account for 42% and 37% of the regional production (Table 87).

575 **Table 87.** Estimated total amount of manure potentially produced annually (in 1000 tonnes on dry matter
 576 basis) across different regions. All values were estimated using FAOSTAT data (see methods).

Continent	Geographic region	Non-dairy	Dairy	Buffalo	Pigs	Broilers	Layers	Ducks	Horses
Africa	Eastern Africa	240031	120362	0	2550	10222	750	528	2869
	Middle Africa	80722	6911	0	1109	4451	91	5	1762
	Northern Africa	52238	40711	3980	5	19224	1184	472	1667
	Southern Africa	29259	4949	0	221	5205	289	26	591
	Western Africa	121460	34941	0	2116	15113	1717	87	2860
Americas	Caribbean	14020	3780	11	550	9762	181	18	2451
	Central America	81531	16973	0	3233	18461	1818	534	10010
	Northern America	172586	32242	0	12609	62529	3140	567	14893
Asia	South America	598417	84428	3450	9312	79881	3305	580	17176
	Central Asia	28592	32850	47	126	2799	476	5	5140
	Eastern Asia	122616	25012	49716	56895	89489	23943	45644	10647
	South-Eastern Asia	87968	15938	24457	11164	165840	5127	13569	1242
	Southern Asia	369829	242073	286745	1478	102379	5349	6009	1451
Europe	Western Asia	29132	32374	1092	125	27461	1734	47	453
	Eastern Europe	41461	45218	91	7467	26523	2856	2885	3192
	Northern Europe	31161	16010	0	3350	5871	634	3853	1014
	Southern Europe	24594	13820	746	6688	2229	242	17	162
Oceania	Western Europe	52432	33624	19	8601	14392	1234	1467	578
	Australia and NewZ	52801	19917	0	365	4024	147	86	402
	Melanesia	791	106	0	336	335	19	8	92
	Micronesia	28	9	0	7	26	2	0	0
	Polynesia	138	10	0	37	35	2	2	22
Total		2231803	822253	370355	128344	666246	54234	76408	78672
Lower 95% CL[†]		1316157	501542	37587	49561	348518	23007	17592	40553
Upper 95% CL[†]		3234190	1209885	806318	239413	1009124	100362	166387	119017

577 [†] Values represent the lower and upper 95% confidence limits estimated using bootstrapping

578

579 3.4. Wood residues

580 Globally, an estimated 0.23 billion tonnes (CL: 0.08–0.43) of wood residues are produced every
 581 year (Table 98), but the largest production occurs in East Asia (China producing the highest)
 582 followed by South America and North America where Brazil and USA have the highest production,
 583 respectively. Annual wood residue production was highest in China (95.1 million tonnes) followed
 584 by Brazil (18.8 million tonnes). The values presented in Table 8 are based on countries for which
 585 data were available in FAOSTAT. Since data are not available for all countries in many regions, it
 586 was not possible to calculate the residue production per country as a proportion of the total

587 production in the respective region. Countries in the Caribbean, Central Asia, Middle Africa,
 588 Western Africa, Northern Africa and Southern Asia are poorly represented (Table 98).

589
 590 **Table 98.** Estimated total annual wood residue potentially produced (in 1000 tonnes on dry matter basis)
 591 across different regions. All values were estimated using FAOSTAT data (see methods).

	Region	Wood residues	Countries where data are available
Africa	Eastern Africa	112	Ethiopia, Kenya, Malawi, Madagascar, Mauritius, Zambia
	Middle Africa	15.7	Cameroon
	Northern Africa	119.1	Sudan, Tunisia
	Western Africa	609.4	Mali, Cote d'Ivoire
	Southern Africa	514.5	South Africa
Americas	Caribbean	0.6	Cuba
	Central America	1044.5	Costa Rica, Guatemala, Honduras, Nicaragua, Panama
	Northern America	22610.3	Canada, USA
	South America	24798.8	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Suriname, Venezuela, Uruguay
Asia	Central Asia	1.5	Kazakhstan, Kirghizstan
	Eastern Asia	101867.0	China, South Korea, Japan
	Southern Asia	3.3	Bhutan, Sri Lanka
	South-Eastern Asia	8815.2	Indonesia, Malaysia, Viet Nam
	Western Asia	966.8	Azerbaijan, Cyprus, Georgia, Israel, Turkey
Europe	Eastern Europe	19810.6	Belarus, Bulgaria, Czechia, Hungary, Moldova, Poland, Romania, Russia, Slovakia, Ukraine
	Northern Europe	19428.2	Estonia, Finland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom
	Southern Europe	4412.3	Albania, Bosnia, Croatia, Greece, Montenegro, Portugal, Serbia, Slovenia, Spain
	Western Europe	18207.5	Austria, Belgium, France, Germany, Luxembourg, The Netherlands
Oceania	Australia and New Zealand	2535.8	Australia
	Total	225873	
	<u>Lower 95% CL[†]</u>	<u>79837</u>	
	<u>Upper 95% CL[†]</u>	<u>426061</u>	

592
 593

594 4. Discussion

595 The preceding sections have presented ~~indicative preliminary~~ estimates of the quantities of
 596 agricultural residues and by-products for selected crops and animals available in the OMD. Due to
 597 the lack of uniform methodology and data across countries, it was not possible to accurately
 598 estimate the quantities of residues produced by all crops and agro-processing activities. We are also
 599 keenly aware that the values presented could either overestimate or underestimate the global residue
 600 production. However, Nevertheless, OMD is a living ~~tool~~-database that will be updated and
 601 enriched as new data and methods become available to build a solid reference resource for industry,
 602 researchers and decision-makers in soil health management, pollution risk reduction, bioenergy

603 production and other sectors. The OMD is envisaged to complement existing databases such as
604 FAOSTAT, FishStat and organic resource quality databases such as Phyllis. -The [residue estimates](#)
605 ~~in~~ OMD may be used for various purposes including estimation of availability for soil amendments,
606 animal feed, bioenergy and other agricultural activities such as mushroom production. The use of
607 agricultural and forestry residues and by-products for soil amendment may be constrained by these
608 competing uses (Duncan et al., 2016; Ji et al., 2018). The following sections will discuss the
609 production and competing uses of agricultural, fisheries and forestry residues, and the opportunities
610 and challenges for their use as soil amendment.

611

612 **4.1. Crop residues**

613 The estimates provided for the selected crops (Table 3) reveal that large quantities of crop residue
614 biomass are produced annually. [However, there are large differences in the share of residues of the](#)
615 [different crops among countries and regions. For example, the largest total annual production of](#)
616 [maize residue was recorded in Northern America, whereas the largest wheat and rice residue](#)
617 [production was recorded in Southern Asia. There are also large differences in the uses of residues](#)
618 [across regions and countries. According to estimates by Smerald et al. \(2023\), about 44% of cereal](#)
619 [residues is left on field, 33% is used for animal feed and bedding, 16% is used for other purposes](#)
620 [and 6% is burnt. In China, which is one of the largest producers of crop residues, 82.3% is currently](#)
621 [collected and used either as fertilizer \(62.3 %\), feed \(16.0 %\), energy \(9.6 %\), cultural substrate \(0.8](#)
622 [%\), or as a raw materials \(1.1 %\) \(Zhao et al., 2024\). In many parts of the world crop residues are](#)
623 [widely used as soil amendments or as a mulch to protect the soil from erosion. Farmers also remove](#)
624 [residues to feed animals or use them as beddings. For example, about 16% of the collectible crop](#)
625 [residues is used as animal bedding in Europe \(Monforti et al., 2013\). In the EU member states](#)
626 [alone, around 28 million tonnes of crop residues are used for animal bedding annually \(Scarlat et](#)
627 [al., 2010\). Crop residues are also used as fuel in industrial and domestic set-ups. For example, in](#)
628 [rural areas in Africa and Asia, crop residues are used for cooking. There is also a growing interest in](#)

629 [the use of crop residues for the generation of biofuels as alternatives to fossil fuels and industrial](#)
630 [applications including textiles, natural fibres, polymers, biosorbents and reinforcement material in](#)
631 [composites \(Siqueira et al., 2022\).](#)

632 The estimated total annual crop residue produced by the top cereal and legume crops across
633 the different regions indicate the high potential for their use in soil amendment and contribution to
634 bioeconomy processes. Depending on the availability of technology for recovery, some of the crop
635 residues produced may be used for recycling in bioenergy production and use as soil amendments.
636 Raw crop residues such as straw can be incorporated into the soil or applied on the soil surface as a
637 mulch, and this can reduce erosion, maintain soil moisture and add carbon and nutrients to the soil.
638 A growing body of meta-analyses have provided compelling evidence that residue retention
639 significantly increases crop yields, soil nutrient stocks, water use efficiency, carbon sequestration,
640 microbial diversity and functionality (Shu et al., 2022; Wang et al., 2020). Significant increases in
641 soil organic carbon (SOC) have been achieved following residue retention relative to inorganic
642 fertilization under residue removal (Wang et al., 2020). This is because soil incorporation of
643 residues provides a direct carbon source for SOC formation. In a global meta-analysis of 219
644 studies, Shu et al. (2022) showed significant improvement in microbial diversity, richness and
645 community structure (by >100%) following application of crop residues compared to mineral
646 fertilization.

647 While crop residues can contribute to enhancing soil organic carbon stocks and nutrient
648 availability to crops, and reduce soil erosion, not all crop residues produced are readily available as
649 a soil amendment. Some of the crop residue is burnt in the field or used as fuel for domestic
650 purposes, for animal feed and/or bedding, mushroom production, construction, industrial
651 applications (FAO, 2022a; Ji et al., 2018). In some cropping systems and regions, residues are
652 burned in the field during land preparation because it is the easiest option for farmers. For example,
653 the intensification of rice cropping with high-yielding and short-duration varieties in Asia has
654 resulted in larger volumes of rice straw, which must be managed over a very short time between

655 two or three cropping rounds per year (Van Hung et al., 2020). In such systems, soil application of
656 residue poses challenges due to the insufficient time for decomposition of the straw, which hinders
657 crop establishment. This has led to an increase in open field burning of rice straw in some Asian
658 countries (Lin and Begho, 2022; Van Hung et al., 2020).

659 Of the residues produced annually, only a small fraction may be recovered because the
660 collection, storage and transportation of raw residues poses challenges for their use outside their
661 production area. One way to reduce the cost of transport and increase their use is to convert bulky
662 residues and by-products into briquettes, pellets, biochar or anaerobic digestate that can be more
663 easily handled and transported than the raw residues (Bora et al., 2020). In some regions, the short
664 time frame between two cropping seasons may not allow collection of the available residues (FAO,
665 2014; 2021). Even when collection is feasible, the cost of transportation may limit soil application
666 far from the farm where the residues were produced. This may be overcome by mechanized
667 collection, high-density compaction, briquetting, pelletizing or on-site processing (e.g., composting
668 or anaerobic digestion). High-density compaction can reduce the volume of crop residues thus
669 making it easier to store and transport over a long distance. For example, the volumetric weight of
670 mechanically compacted rice straw bales is 50–100% higher than that of loose straw. Briquetting
671 and pelletizing can further increase the volumetric weight of baled straw by up to 700% and reduce
672 transportation costs by more than 60% (Balingbing et al., 2020).

673 The quality of residues may play a critical role in the build-up of carbon and nutrients in the
674 soil (Cotrufo et al., 2013) against the backdrop of the importance of the soil ecosystem (Schmidt et
675 al., 2011). The carbon content of residues is about 30-50% (Table 1). The nitrogen content of
676 various cereal straws ranges between 0.3 and 2.8%, and only pulse straws are relatively nitrogen-
677 rich (Table 1). With low C:N ratios (Table 1), residues from legumes are likely to decompose more
678 rapidly than cereals. The phosphorus and potassium content of most residues is 0.05-0.3% and 0.2-
679 2%, respectively (Table 1). As such, crop residues represent a substantial store of carbon and
680 nutrients that can be used as inputs for soil amendment. A role of crop residue incorporation that

681 has remained less appreciated is their contribution to soil micronutrient stocks especially sulphur,
682 calcium, magnesium, zinc and silicon that are often not part of the recommended fertilizers. Where
683 straw is incorporated, reserves of soil nitrogen, phosphorus, potassium and silicon have also known
684 to be maintained at acceptable levels (Dobermann and Fairhurst, 2002).

685

686 **4.2. Agro-processing by-products**

687 Our estimates indicate that substantial quantities of by-products are produced every year, but with a
688 great deal of variability across regions. Unlike crop residues, most of the by-products are produced
689 in localized processing plants, which makes their collection more convenient. However, some of the
690 by-products may not be available for soil amendment as they have various [other](#) uses. For example,
691 husks of rice ~~and sugarcane bagasse~~ are mostly used as fuel in the rice ~~and sugar~~ mills ([Petersen et](#)
692 [al., 2015](#)). Rice husk is also used as an insulating material. In crops such as oil palm, cocoa and
693 coffee, the processing also occurs in a few countries where the commodities are grown on
694 commercial scale.

695 Although oil palm is widely cultivated in plantations across the humid tropics of Asia, Africa
696 and the Americas, over 90% of the global palm oil production occurs in just five countries, namely,
697 Indonesia (58.8%), Malaysia (25.6%), Thailand (3.9%), Colombia (2.9%) and Nigeria (1.4%)
698 (Murph et al., 2021). Although the oil palm industry is one of the best sources of organic inputs for
699 agricultural use (Adu et al., 2022; Embrandiri et al., 2012), the residues may not be available for
700 direct soil application in areas far from processing plants. However, this can be circumvented
701 through conversion into compost or digestates, which are easier to handle and transport.

702 [Our global estimate of sugarcane bagasse production \(548.7 million tonnes is very close to](#)
703 [the 540 million tonnes reported in Bezerra and Ragauskas \(2016\). Unlike other crop residues,](#)
704 [bagasse is not readily available for soil amendment. This is because much of the bagasse produced](#)
705 [is used for steam generation in sugar mills and the remainder is burnt as dry bagasse is known to be](#)
706 [a fire hazard. Bagasse consists roughly of 20–30% lignin, and 40–45% cellulose and 30–35%](#)

707 [hemicellulose, making it a promising feedstock for second-generation biofuel production \(Bezerra](#)
708 [and Ragauskas, 2016; Petersen et al., 2015\)](#). In some countries bagasse is also used as a raw
709 [material for the paper and board industry](#).

710 [While slaughterhouse operations produce large quantities of by-products, some of are](#)
711 [processed by the rendering industry for conversion into animal feed, pet food, poultry meal and](#)
712 [animal fats \(Mozhiarasi and Natarajan, 2022\)](#). ~~As with crop residues, there~~ There are challenges to
713 the availability of by-products from [slaughterhouse and](#) fish processing [facilities](#) for soil
714 application. [Different parts of animal such as head, feet, fat, and blood can be used in a variety of](#)
715 [ways, and therefore may not be readily available for soil amendment](#). Some fish parts, especially
716 viscera, deteriorate very rapidly and therefore they require preserving as soon as possible after
717 being produced. This is not always possible due to inadequate processing facilities or limited
718 volumes making recovery of the by-products unprofitable. When fish are processed to fillets at sea,
719 viscera, the head and frames are often discarded since refrigeration facilities are used for the most
720 valuable product (Olsen et al., 2014).

721

722 **4.3. Livestock manure**

723 Our estimates in Table 7 show that large quantities of manure are produced annually albeit large
724 variability across regions. These estimates include both manure management systems and manure
725 left on pasture. Only a fifth of livestock manure produced is ~~returned-applied to on cropland soil~~ due
726 to various constraints. For example, much of the manure produced may not be available for
727 application as soil amendment [on cropland](#) because over 70% is directly deposited on pasture
728 (FAO, 2018). Manure applied to soil can be a significant source of macronutrients and
729 micronutrients (FAO, 2018; Sileshi et al., 2019). In addition, manure is a significant source of
730 organic matter, which is a key determinant of soil health (FAO, 2018). For example, globally
731 manure applied to soil was estimated to contribute 24 and 31 million tonnes of nitrogen per annum
732 based on IPCC Tier 1 and Tier 2 approaches, respectively (FAO, 2018). According to van Dijk et

733 al. (2016), manure application on soil constitutes approximately 53% of the P and 33% of the N
734 applied annually to agricultural land in the EU27.

735 Even if manure is available in abundance, its application may be constrained by
736 environmental quality and economic considerations in some jurisdictions. For example, in the USA,
737 the Environmental Protection Agency regulation requires large animal feeding operations to meet
738 nutrient planning requirements for land application of manure. Similarly, according to the EU
739 Council Directive 91/676/EEC, the amount of livestock manure applied to land each year shall not
740 exceed 170 kg N per hectare. Legislation may also forbid manure application during certain periods
741 (e.g., in non-cropping seasons) or land that would otherwise lead to environmental impact through
742 run off or nutrient leaching (Loyon, 2018).

743 The bulky nature of manure limits the areas over which it can be economically applied.
744 According to Paudel et al. (2009), the economically optimal distances for dairy manure application
745 is 30 km for nitrogen and 15 km each for phosphorus and potassium to meet the recommended N,
746 P₂O₅ and K₂O needs on cropland. Conversion of manure into anaerobic digestate or compost can
747 circumvent the handling, storage and transportation costs of raw manure from intensive animal
748 production units. When efficiently managed and recycled within agricultural systems, livestock
749 manure represents a large source of plant nutrients that can reduce the need for synthetic fertilizer
750 inputs and reduce GHG emissions (FAO, 2018). Manure may be applied by injection, band
751 application, surface spreading or incorporation (Emmerling et al., 2020). Injection has been cited as
752 the best application method to reduce NH₃ emissions, while surface application using splash plates
753 has been banned in most European countries because of its strong impact on NH₃ emission
754 (Emmerling et al., 2020).

755

756 **4.4. Wood residues**

757 Wood residues are obviously underestimated for many regions because data were unavailable for
758 some countries. Among the countries for which data exist, annual wood residue production was

759 highest in China and Brazil, representing 42% and 8.3% of the annual global wood residue
760 production. Wood log production in Brazil generates about 50.8 million m³ of lignocellulosic
761 residue yearly (Domingues et al., 2017). Assuming a wood density of ~450 kg m³ this value is
762 approximately 22.9 million tonnes, which is slightly higher than 18.8 million tonnes in our
763 database. [The competing uses of wood residues include use as woodfuel for domestic purposes](#)
764 [\(Flammini et al., 2022\), bioenergy generation \(Karan and Hamelin, 2020\) and as raw materials for](#)
765 [the manufacture of agglomerated products such as pulp, particle board and fibreboard \(FAO,](#)
766 [2022f\)](#). Although wood residues could be potentially used for soil amendment after processing (e.g.,
767 wood-ash, biochar, compost, etc.), the proportion actually available may be small due to their
768 various competing uses. Agroforestry trees and plantation crops such as coconut, oil palms, and
769 rubber generate considerable amounts of woody and leafy biomass from pruning and lopping. A
770 large proportion of such residues can be used for soil amendment directly or after processing into
771 compost or biochar (Bluhm and Lehmann, 2023). However, data were not readily available for
772 these residues, and therefore it was not possible to collate their quantities in the OMD.

773

774 **5. Limitations of the OMD and challenges ahead**

775 One of the key limitations of [this work is the lack of country-specific data on the quantities of the](#)
776 [some categories of residues such as crop processing by-products and manure. Country-specific](#)
777 [conversion factors or equations are also lacking to convert production statistics to residue](#)
778 [data.](#)~~OMD is~~ [As a result we were forced to use a single conversion factor or a single equation in](#)
779 [some cases. A second limitation of this work is](#) our inability to provide global estimate of all
780 residues from agriculture, fisheries and forestry. ~~There are also uncertainties associated with the~~
781 ~~estimates presented.~~ The effort to compile estimates of [all quantities of](#) residues and by-products
782 was hampered by the lack of methods for conversion of primary products to residues and industry
783 standards for collection and aggregation of such data. For example, we did not included the
784 quantities of residues produced by minor crops, fruit trees and other trees in agroforestry and

785 forestry. A third limitation of this work is that we were unable to account for situations where products
786 are processed in a different country than their origin as this would entail additional data on export
787 and import. This could be considered an important future endeavour in the development new
788 versions of the OMD.

789 The OMD also does not contain the quantities of by-products such as biochar, compost and
790 digestate produced in each country due to lack of data ~~and reporting frameworks~~ on their
791 production. By-products of secondary processing that occurs in the breweries and beverage industry
792 could also not be compiled due to lack of data. By-products from capture fisheries were estimated
793 only for a few species because conversion factors were unavailable for the majority of species. Even
794 for those species where conversion factors were available, residues from capture fisheries were
795 probably underestimated by a large margin because recovery of inedible parts is challenging. This is
796 because ~~the~~ fish are processed at sea, and non-edible parts may be discarded in the sea (Olsen et al.,
797 2014). Commercial fish products are often directly processed on-board vessels and, by the time they
798 are landed, the fish have been frozen, gutted, headed, and/or processed, leading to a considerable
799 change from their original weight. This leaves a great deal of uncertainty about estimation of
800 fisheries by-products. We were also unable to provide uncertainties associated with estimates of the
801 quantities presented at national or sub-national level due to the lack of data. Therefore, we strongly
802 recommend investment in the inventory of agricultural, fisheries and forestry residues, by-products
803 and wastes at the national and sub-national levels for use in a circular bio-economy.

804 This work only provides an inventory of the various residues at the country level, which is
805 valuable in its own right. However, further work needs to be done to produce a global map of
806 carbon and nutrients from residues at much greater spatial distribution and finer resolution than
807 individual countries to inform policy and good practice for more efficient allocation of biomass
808 resources. There is also an urgent need for documenting the alternative uses of the various
809 categories of residues estimation of the share of different uses of each residue and unused or wasted

810 [residues at the national and local levels](#). This requires further work and deemed outside the scope of
811 this publication.

812 Due to lack of basic data, this work was unable to determine the proportion of the residues in
813 each category that is actually available for use as soil amendment. Even where data were available,
814 legislative and regulatory issues may limit their use as soil amendments. For example,
815 environmental concerns of pollution by antibiotics, heavy metals and pathogens have led to
816 regulations on direct spread of manure on land (Font-Palma, 2019). Strict regulations such as those
817 under the EU Nitrates Directive 91/676/EEC (EEC, 1991) mean that only a small proportion of the
818 total volume of manure produced can be used for soil amendment. It is also forbidden to apply
819 manure or anaerobic digestate at particular times in the year or on certain types of land (Loyon,
820 2018). In some jurisdictions, organic matter that has been designated as waste may be subject to
821 regulatory restrictions on how it can subsequently be used or managed (Loyon, 2018). In this
822 analysis, it was not possible to evaluate the extent to which national policies and regulatory
823 frameworks governing the classification of organic matter streams as wastes or by-products, and
824 waste management can provide incentives or not to the use of organic inputs for soil amendment.
825 Legislation banning residue burning and incentives for farmers to adopt good agricultural practices
826 can also incentivise appropriate use of agricultural residues. For example, EU Regulation No
827 1307/2013 has established rules for direct payments to farmers under support schemes within the
828 framework of the common agricultural policy. To receive full payments, farmers in the member
829 states have to comply with statutory management requirements and standards for good agricultural
830 and environmental conditions, and the requirements of ‘greening’ (Heyl et al., 2021). Quantitative
831 targets are used to incentivize the implementation of agricultural practices that increase SOC stocks
832 (Bruni et al., 2022). For example, the EU Mission Board for Soil Health and Food proposed a series
833 of quantitative targets for soils to become healthier. Among them, the current SOC losses of about
834 0.5% per year in the 20 cm soil depth of croplands should be reversed to an increase of 0.1–0.4%

835 per year by 2030 (Bruni et al., 2022). Such targets and related regulations will have implications for
836 how and where agricultural residues can be used for soil amendment.

837 Transport costs may also hinder the use of the excess volume produced in one region in other
838 regions. In some regions, anaerobic digestate is produced in excess of its agricultural assimilation
839 potential (Torrijos, 2016). For example, in the EU digestate production reached 56 million tonnes
840 per annum by 2010, of which 80% could be recycled back into agriculture (Kizito et al., 2019).
841 Similarly, in China the annual digestate production is approximately 2.3 billion tonnes of which less
842 than 70% is recycled back to agriculture due to land limitations (Kizito et al., 2019). These
843 observations highlight the need to explore opportunities for use of residues and by-products outside
844 the country where they are produced.

845

846 **Data availability:** The OMD data is available at: <https://doi.org/10.5281/zenodo.10450921>
847 (Sileshi et al., 2024).

848

849 **6. Conclusions**

850 This work has provided typologies, definitions and quantities of the various agricultural residues
851 and by-products, which can be useful for the inventory and estimation of the various residue
852 streams potentially available for recycling in agriculture, bioenergy and other sectors. The OMD is
853 the first of its kind to consolidate biomass estimates of residues and by-products from agriculture,
854 fisheries, forestry and allied industries globally. The OMD will be continuously updated as new
855 production data are published in FAOSTAT and will be publicly available for use by different
856 decision-makers. It is hoped to contribute to the Better Production and Better Environment
857 dimensions of FAO's Strategic Framework 2022-2031 supporting the 2030 Agenda. The OMD and
858 associated products are also expected to contribute to evidence-based policies and actions in support
859 of the transition towards a circular economy, and more sustainable agriculture and food systems.
860 Currently, the estimates in OMD are available only at the national level. Therefore, finer scale data

861 are urgently needed for spatial targeting of residues and by-products for various applications.
862 Detailed site-specific inventory of various categories of residues and their local uses are highly
863 recommended.

864

865 **Authors' contributions**

866
867 EB, GWS, FNT conceptualized and designed the study. GWS, JL developed the methodology and
868 GWS conducted data curation and formal analysis. GWS, EB wrote and edited the manuscript,
869 while JL, FNT reviewed and edited the manuscript. EB funding acquisition. All authors have read
870 and approved the final version of the manuscript.

871 **Competing interests**

872 One author (FNT) is a Topical Editor of *Earth Systems Science Data*.

873 **Disclaimer**

874 The views expressed in this paper are the authors' only and do not necessarily reflect those of FAO.
875

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882

883

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