1 **Organic Matter Database (OMD): Consolidating global residue data from**

2 **agriculture, fisheries, forestry and related industries**

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16 **Abstract**

17 Agricultural, fisheries, forestry and agro-processing activities produce large quantities of residues,

18 by-products and waste materials every year. Inappropriate disposal and inefficient use of these

19 resources contributes to greenhouse gas emissions and non-point pollution, imposing significant

20 environmental and economic burdens to society. Since many nations do not keep statistics of these

21 materials, it has not been possible to accurately quantify the amounts produced, their competing

22 uses and the quantities potentially available for recycling at local level. Therefore, the objectives of

23 the present work were to provide: (1) definitions, typologies and methods to aid consistent

24 classification, estimation and reporting of the various residues and by-products; (2) a global organic

25 matter database (OMD) of residues and by-products from agriculture, fisheries, forestry and related

26 industries; and (3) regional and global estimates of residues and by-products potentially available

27 for use in a circular bio-economy. To the best of our knowledge, the OMD is the first of its kind

28 consolidating quantities and nutrient concentrations of residues and by-products from agriculture,

29 fisheries, forestry and allied industries globally (available at:

30 https://doi.org/10.5281/zenodo.10450921). The OMD will be continuously updated as new

31 production data are published in FAOSTAT and country-specific conversion coefficients become

32 available. This information is expected to contribute to evidence-based policies and actions in

33 support of sustainable utilization and the transition towards a circular economy. The database could

34 be used for a variety of purposes including estimation of residue availability for soil amendment,

35 livestock feed, bioenergy and other industrial applications, and assessment of environmental

36 impacts of residue management practices such as soil application and burning. The estimates in

37 OMD are available only at the national level. Due to the lack of uniform methodology, conversion

38 coefficients and data on competing uses across countries, it was difficult to accurately estimate the

39 quantities of all agricultural, fisheries and forestry residue and by-products. Therefore, we strongly

40 recommend investment in the inventory of agricultural, fisheries and forestry residues, by-products

41 and wastes at the national and sub-national levels for use in a circular bio-economy.

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 (CH_4) and 32 kilo tonnes of nitrous oxide (N_2O) 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).

69 Conversely, a significant portion of these residues could enter a circular bio-economy, and their

70 efficient use can ensure achievement of sustainability goals, through reduction of GHG emissions

71 and non-point pollution.

72   Agricultural residues are used in many different ways including soil amendment, for animal

73 feed and bedding, bioenergy generation, as fuel in industrial and domestic set-ups, mushroom

74 production, industrial applications such as textiles, natural fibres, polymers, biosorbents and

75 reinforcement material in composites (Siqueira et al., 2022; Smerald et al., 2023; Zhao et al., 2024;

76 see also discussion under sections 4.1−4.4). A growing body of evidence suggests that currently

77 unused residues could in principle be more effectively managed to increase soil fertility and

78 productivity, and to mitigate greenhouse gas emissions (Lu et al., 2014; Liu et al., 2015).

79   Over the years, agriculture has increasingly depended on synthetic fertilizers to meet crop

80 nutrient demands. The increased fertilizer use and inefficient fertilizer management practices have

81 led to large nutrient losses to the environment in some regions (FAO, 2022b; Singh and Craswell,

82 2021). On the other hand, farmers in low-income countries have limited access to fertilizer inputs,

83 and this has led to depletion of native soil nutrient stocks from croplands. Access to fertilizers has

84 been further limited by the recent war by Russia on Ukraine, which disrupted a large portion of the

85 global fertilizers supply. The resultant increases in prices are likely to constrain fertilizer use by

86 farmers into the foreseeable future (FAO, 2022c; Behnassi and El Haiba, 2022). In 2020, the

87 production and use of synthetic fertilizers resulted in GHG emissions of 1.0 Gt CO_2 equivalent, of

88 which 62% (or 0.63 Gt CO_2) is emitted when nitrogen fertilizers are used on croplands (FAO,

89 2022d; Tubiello et al., 2022).

90   A growing body of evidence from meta-analyses suggests that the combined use of organic

91 inputs and inorganic fertilizers can increase fertilizer use efficiency (Ba et al., 2022; Chivenge et al.,

92 2011; Sileshi et al., 2019; Wang et al., 2020; Zhang et al., 2020; Melo et al., 2022). There is also a

93 growing consensus that judicious use of agricultural residues can partially substitute for inorganic

94 fertilizers (Fan et al., 2021; Huang et al. 2013; Zhang et al., 2020) and thereby contribute to

95   enhancing the sustainability of food production by reducing costs and carbon footprints while

96   reducing pollution caused by nitrate leaching (Zhang et al., 2020). The savings resulting from

97   recycling agricultural residues and wastes can also be an important contribution to national and

98   local economies. Recycling of organic residues, by-products and wastes can also address waste

99   management problems and reduce GHG emissions from residues and wastes (Andrews et al., 2021;

100   FAO, 2022a).

101   Yet, the potential contributions of agricultural, fisheries and forestry residues and by-products

102   to soil health improvement and carbon management has not been estimated fully. This is largely due

103   to a lack of country statistics on the production of residues and by-products from agriculture,

104   fisheries and forestry, which makes it difficult to accurately quantify the amounts produced and

105   available for recycling. The designation of residues as a resource, by-product or waste may also not

106   always align with how the material is subsequently managed or its potential utility as a soil

107   amendment. For example, livestock manure may be classified as a waste in some jurisdictions but

108   not in others, whether or not it is subsequently used as an organic fertilizer. Importantly, a clear

109   typology of residues and by-products also does not exist in many regions. This hinders the

110   systematic documentation and reporting of the different categories of organic resources.

111   Information is also scant on the quality of most of the residues produced. The quality of organic

112   resource varies with the plant species, plant parts and their maturity level (Palm et al., 2001; Cobo

113   et al., 2002), and determination of the quality attributes using traditional laboratory methods is both

114   timely and costly (Shepherd et al., 2003). Despite these challenges, Palm et al. (2001) published an

115   organic resource database containing data on plant species and plant part, resource quality,

116   decomposition rates, N release rates, digestibility indices and site characteristics. Rapid plant

117   nutrient analysis based on spectroscopic methods have been developed (Shepherd et al., 2003), and

118   complemented with methods assessing functional differences (e.g., carbon and nitrogen release

119   rates, digestibility) (Vanlauwe et al., 2005). Additional efforts to make this organic resource data

120   useful included a decision support system for different categories of organic resources (Palm et al.,

121 2001; Vanlauwe et al., 2005). A related effort is the Phyllis database developed by the Energy

122 Research Centre of the Netherlands (ECN, 2018) primarily focussing on biomass properties that are

123 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 estimates of the different

137 residues and by-products is urgently needed for practitioners and policy-makers to quickly refer to

138 when making decisions. Accordingly, the objectives of the present work were to provide: (1)

139 definitions, typologies and methods to aid consistent classification, estimation and reporting of the

140 various residues and by-products; (2) a global organic matter database of residues and by-products

141 from agriculture, fisheries, forestry and related industries; and (3) regional and global estimates of

142 residues and by-products potentially available for use in a circular bio-economy. Wherever possible,

143 this work also tried to highlight the competing uses of the various residues and the challenges and

144 opportunities for their use as soil amendments. The database could be used for a variety of purposes

145 including estimation of availability of residues for livestock feed, soil amendment, bioenergy

146 production, industrial applications, and assessment of environmental impacts (e.g., pollution,

147 greenhouse gas emissions, nutrient flows) of residue management practices (e.g., residue retention,

148 burning, and disposal).

149

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.

156
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 (in tonnes live weight) came from FAO's FishStatJ statistical software

167 (https://www.fao.org/fishery/static/FishStatJ) for the periods 2015–2019 for selected species in each

168 country/territory. In all cases, production refers to the total quantity produced per country in a given

169 year.

170 　　　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 available at:
186   https://doi.org/10.5281/zenodo.10450921.

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

187   * Represents IPCC default values
188

189   **2.2. Definitions and typology**

190   The literature reviewed identified many sources of organic input that can be used for soil

191   amendment. These include crop residues, agro-processing by-products, forestry and logging

192   industry residues, manure, poultry and meat processing and fisheries and aquaculture by-products.

Authors have used the terms 'residue', 'by-product', 'co-product', 'waste', when referring to the various organic resources. Therefore, it was necessary to provide clear definitions and typologies (systematic classification) to facilitate their consistent estimation and compilation in the OMD. A 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 as a substance or object whose primary aim is not the production of that item, whereas "waste" is defined as any substance or object which the holder discards, intends to discard, or is required to discard. According to the Directive, an object or substance should be regarded as a by-product only when certain conditions are met as specified under Article 5. In this paper, this norm was followed and the term "by-product" was consistently used to refer to side products originating from the food manufacturing stage. By-products may be products of either primary or secondary processing of 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 included in the OMD as they consist of a wide variety of materials that may be required to be disposed of in accordance with local legislation. Crop residues, agro-processing by-products, manure and forestry residues were included in the OMD.

2.2.1. Crop residues

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

2.2.2. Agro-processing by-products

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

219 oil presses and bioenergy production, slaughterhouse by-products and fish processing by-products,

220 which are further defined below.

221

222 *2.2.2.1. Cereal processing by-products*

223 Cereal processing by-products are defined here as the by-product of rice milling and the multi-stage

224 process of flour production from cereals such as wheat, rice and maize. In the milling process of

225 rice, the husk (hull), which is the outer cover of the grain, is removed. Further milling removes the

226 bran resulting in white rice. Rice husk constitutes about 20% of the dry weight of rice grains (Singh,

227 2018). The bran is part of cereal grain that could be used in a further milling process or as a

228 biorefinery feedstock (Caldeira et al., 2020).

229

230 *2.2.2.2. Sugar industry by-products*

231 The by-products from the sugar industry include bagasse, sugar beet pulp, molasses, and filter press

232 mud, which are available at the milling and refining facilities. Bagasse is the fibrous residue

233 remaining after the milling of cane stalks for juice extraction, and it is roughly 27–28% dry weight

234 of the plant biomass (Bezerra and Ragauskas, 2016). The residue to product ratios (RPR) of bagasse

235 was reported to vary from 0.14 to 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 $\sim$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 by- grape

242 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 (Iriondo-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 (Iriondo-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, fibber, 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) bout 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 consist of poultry and meat processing by-products. The inedible parts

316 of slaughtered animals vary with the species, ranging from 22% for turkey, 37% for broilers, 38-

317 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

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

2.2.3. Livestock manure

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

2.2.4. Forestry residues

Forestry residues can be divided into primary and secondary residues (Karan and Hamelin, 2020). Primary residues are defined as residues that are left after logging operations (e.g., branches, stumps, treetops, bark, etc.), whereas secondary residues are by-products and co-products of industrial wood-processing operations (Karan and Hamelin, 2020). Primary residues were excluded 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

2.3. Estimating the quantities produced

356 Crop residue production is typically estimated from grain yield using the harvest index (Smerald et

357 al., 2023). The challenge with this approach is that the harvest index varies widely in response to

358 genetic, environmental and agronomic factors, and hence universally applicable harvest indices are

359 lacking at the country level. As a result, practitioners often use residue to product ratios (RPR) to

360 estimate residue biomass from data on production of primary products obtained from local statistics

361 or global databases such as FAOSTAT and EUROSTAT (e.g., Bentsen et al., 2014; Bedoić et al.,

362 2019; Karan and Hamelin, 2021; Ronzon and Piotrowski, 2017). The estimation is sometimes done

363 assuming a mathematical relationship (e.g., linear, logarithmic, hyperbolic or exponential) between

364 the primary crop yield and the residue yield (Bentsen et al., 2014; Ronzon and Piotrowski, 2017;

365 Smerald et al., 2023). The disadvantage of the RPR is that it is constant over time and space for a

366 given crop, whereas methods based on mathematical functions can be more flexible. In this work,

367 the estimation of residues and by-products generally followed IPCC guidelines (IPCC, 2019) and

368 the FAO guidelines in the Bioenergy and Food Security Rapid Appraisal user manual for crop and

369 livestock residues (FAO, 2014).

370 In the case of crop residues, country-specific harvest indices or RPRs are not available for

371 almost all countries. Therefore, the IPCC approach was used for estimating crop residues from

372 harvested produce. The IPCC provides two alternative methods for estimation of the aboveground

373 crop residue yield ($AG_{DM(T)}$) in kg ha^{-1} on dry mass basis. The first method involves multiplying the

harvested crop yield with the ratio of aboveground dry matter ($R_{AG(T)}$) provided in Table 11.A of

IPCC (2019). The second method involves estimation of residue yields from crop yield using linear

equations in Table 11.2 (IPCC, 2019). For any given crop (T), the following two methods were

available based on the exact IPCC notations:

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

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

The first method always yields a constant harvest index, and most of the times it yields larger than

the typical values reported in the literature (e.g., Ludemann et al., 2023). For example, the IPCC

default values of $R_{AG(T)} = 1$ and 1.2 for maize and barley yield harvest indices of 0.50 and 0.47,

while the typical values are less than 0.47 and 0.41, respectively. As a result, the first method

systematically underestimates residue production relative to the second method. The advantage of

the second method is that it yields a more realistic harvest index commensurate with the grain yield

achieved in a particular country and year. Therefore, the second method was chosen for estimating

$AG_{DM(T)}$ from $Crop_{(T)}$ in FAOSTAT for the period 2015-2020. Then, the total annual above-ground

residue production ($AGR_{(T)}$) was calculated for each crop (T) by multiplying $AG_{DM(T)}$ by the

harvested area available in FAOSTAT per country and year for maize, wheat, rice, barley, soybean

and groundnut. The average values of six years (2015–2020) per country were summed across

countries to provide annual aboveground residue production estimates ($AGR_{(T)}$) in tonnes on dry

matter basis) for each region. Then these values were added to produce a global estimate of total

residue production. The uncertainty around each estimate was expressed with 95% confidence

limits (CLs). It is not possible to generate estimates such as the standard errors or 95% confidence

limits of the sum of quantities using conventional statistical methods. Therefore, the 95% CLs were

estimated using bias-corrected bootstrapping, a non-parametric method which involves random

resampling of the sample totals (sum) with replacement.

399 **Table 2**. The IPCC equations used for estimation of above-ground crop residue yield ($AG_{DM(T)}$) in tonnes per

400 ha) from grain yield ($Crop_{(T)}$ in tonnes per ha) from FAOSTAT, and IPCC default values for dry matter

401 fraction of harvested product and dry matter fraction of aboveground crop residue.

Crop	IPCC equation for $AG_{DM(T)}$[†]	IPCC default values	
		Dry matter fraction of harvested product ($R_{AGR(T)}$)[†]	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

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

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

404

405   Production of agro-processing by-products is often estimated using country-specific

406 coefficients following the FAO guidelines (FAO, 2014). Wherever available, these values defined

407 as extraction rates, were obtained from FAO's Technical Conversion Factors for Agricultural

408 Commodities (FAO, 2009). When not available, average values from the literature were used for

409 estimating the various by-products from the production data in FAOSTAT. For example, the

410 median value of 0.29 from Koopmans and Koppejan (1998) was used to estimate bagasse from

411 sugarcane.

412   Poultry processing by-products were estimated using country-specific take-off rates, dressed

413 carcass weight (% of live weight) and stocks (heads) as follows:

414 *Residue = (take-off rate/100)*average live weight*(100-% carcass weight)*stocks*

For each poultry species (chickens, ducks, geese and turkeys) in each country/territory, the take-off

rate (in %), average live weight (kg/animal), and dressed carcass wet weight (in %) were obtained

from FAO's Technical Conversion Factors for Agricultural Commodities (FAO, 2009), while

stocks (number of animals) were obtained from FAOSTAT Crops and livestock products

(https://www.fao.org/faostat/en/#data/QCL).

Similarly, meat processing by-products were estimated using country-specific take-off rates,

dressed carcass weight (% of live weight) and stocks (heads) as follows:

Residue = (take-off rate/100)*average live weight*(100-% carcass weight-% hides/skins-%edible

offal)*stocks

The dressed carcass weight is the weight of the carcass after removal of hide/skin, head, feet, offal,

raw fats, and blood which is often not collected in the course of slaughter. For each species

(buffaloes, cattle, sheep, goats, horses, camels and pigs) in each country/territory, the take-off rate

(in %), average live weight (kg/animal), and dressed carcass wet weight (in %) were available in

FAO's Technical Conversion Factors for Agricultural Commodities. As in the poultry species,

stocks were available in FAOSTAT Crops and livestock products for each country/territory.

Carcass weight, edible and non-edible offal was used as defined in FAO's Livestock statistics:

Concepts, definitions and classifications (FAO, 2011). According to the definition in FAO (2011),

edible offal in most countries include head or head meat, throat bread, thick skirt, tongue, sweet

bread, genital organs, brains, lungs, udder, feet, liver, stomach or tripes, tail meat, spleen, blood,

heart and diaphragm. In this calculation, the non-edible portions are assumed to be disposed off in

slaughter houses and these were considered as residues. However, in certain circumstances parts

such as head, feet, fat and blood can be used in a variety of ways. Since data are not available from

slaughter houses on specific uses of non-edible offal, we were unable to establish the alternative

uses.

Residues from capture fisheries and aquaculture species were estimated using country-

specific conversion factors available in the Handbook of Fishery Statistical Standards (CWP, 2004)

441 for selected species. In the fisheries industry, the term "conversion factor" is used principally when

442 converting the volume or mass (more commonly referred to as the "weight") of a product at one

443 stage to its volume or mass at another stage in the chain (FAO, 2004). Conversion factors for a

444 particular state of processing vary according to species and state of processing. The state of

445 processing is hierarchical, and may consist of the following categories: (a) gutted, (b) headed and

446 gutted, (c) dressed, (d) fillet (skin on or off), etc. The FAO global inland and marine capture

447 database includes catches for over 2000 species/items (including the "not elsewhere included"

448 categories). Since conversion factors are not available for all species, first species were ranked

449 based on the number of countries producing and the total production in 2019. Then the top 6 species

450 were selected for the present analysis because of availability of conversion factors and the large

451 number of countries involved in their production. Among the aquaculture species, rainbow trout

452 (*Oncorhynchus mykiss*) was chosen as it was the topmost grown in aquaculture in 91 countries. In

453 capture fisheries, yellow fin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*),

454 swordfish (*Xiphias gladius*), Bigeye tuna (*Thunnus obesus*) and albacore (*Thunnus alalunga*) were

455 chosen for the analysis. Each of these species were harvested in 96, 90, 83, 79 and 71 countries,

456 respectively. The production quantity was then converted to residues as follows: Value-(Value/CF)

457 where CF is the indicative factors for converting product weight to live weight. The FAO database

458 of capture fisheries production covers only retained catches; data on by-catch (discarded catches)

459 are not included (Garibaldi, 2012). This means that the by-products can be severely underestimated.

460   Manure production (in tonnes/year on dry matter basis) was estimated from manure excretion

461 rate (kg/head/day on dry-weight basis) and stocks (from FAOSTAT) following the FAO guideline

462 for the different animal categories (FAO, 2014). The general formula for manure production is as

463 follows:

464 *Manure production (tonnes/year) = (365*stocks*manure excretion rate)/1000*

465 Since there is no global database which provides country-specific data on manure production, the

466 FAO tool uses the IPCC default values (FAO, 2014). For each species, average manure excretion

467 rates were obtained from values compiled from the literature. For the USA, excretion rates were

468 obtained from ASAE Standards D384.1 of the American Society of Agriculture Engineers (ASAE)

469 Manure production and characteristics (2005). Manure production was estimated for different

470 management systems of cattle (non-dairy and dairy) and chicken (broilers and layers) separately

471 because these are always managed as separate enterprises.

472 When compiling forestry residues, primary residues were excluded because of the concerns

473 related to the environmental and economic sustainability of removing them from the forest for soil

474 application on farm-land. Therefore, the analysis focused on wood residues following the FAO

475 definition. Country-specific data on production quantity of wood residues (item code 1620) in

476 FAOSTAT (https://www.fao.org/faostat/en/#data/FO) were used for compiling the OMD. These are

477 reported in cubic meters solid volume excluding bark on FAOSTAT.

478 A database of all the coefficients and RPR used in the estimation of the various residues and

479 by-products is now available in the OMD.

480

481 ## 3. Results

482 ### 3.1. Crop residues

483 Maize had the largest global total annual above-ground residue production (~1.28; CL: 0.43–2.33

484 billion tonnes) followed by wheat (~1.25; CL: 0.66–1.91 billion tonnes) and rice (~1.11; CL:

485 0.09–1.93 billion tonnes) (Table 3). The estimated quantities of crop residue varied widely by

486 continent and region. For example, the largest total annual production of maize residue was

487 recorded in Northern America including Canada and USA (~0.41 billion tonnes) followed by

488 Eastern Asia (~0.30 billion tonnes) including China, Democratic People's Republic of Korea, South

489 Korea and Japan; China accounted for over 99% of the residues produced in Eastern Asia. The

490 largest wheat residue production was recorded in Southern Asia (~0.24 billion tonnes) including

491 Afghanistan, Bhutan, India, Iran, Nepal and Pakistan and Sri Lanka, of which over 67% was

492 produced in India. Rice residue production was highest in Southern Asia (~0.38 billion tonnes), of

493   which over 70% was produced in India. The global total annual residue production from soybean

494   was ~0.49 million tonnes, while for groundnuts the corresponding value was ~0.10 billion tonnes

495   (Table 3). The largest soybean residue production was recorded in South America (~0.25 billion

496   tonnes) of which Brazil accounted for 61% of soybean residue production in that region. This was

497   followed by Northern America (~0.16 billion tonnes) of which USA accounted for 94% of soybean

498   residue production in Northern America.

499

500

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

	Geographic region	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**
	Lower 95% CL[†]	428190	663830	93059	107947	89264	41188
	Upper 95% CL[†]	2328569	1905111	1931334	244998	933898	163731

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

504

3.2. Agro-processing by-products

3.2.1. By-products from processing crops

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

production in South America. Similarly, India accounts for 80.3% of the annual bagasse production

in Southern Asia.

The global annual production of by-products of coffee, cocoa and oil palm processing were

estimated at 20.5, 5.3 and 170.1 million tonnes (Table 4). The largest quantity of coffee-processing

by-products was recorded in South America, with Brazil producing about 6.5 million tonnes

accounting for over 71% of the annual production in South America. This was followed by South-

Eastern Asia, where Viet Nam produced 3.3 million tonnes annually. The largest quantity of by-

products from cocoa was produced in West Africa, where Cote d'Ivoire accounted for over 60% of

the production in that region. Out of the 170.1 million tonnes of global annual oil palm by-products,

Indonesia accounted for over 59% of the total annual global production.

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

	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**

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

Table 5. Estimated total annual production of agro-processing by-products of coffee, cocoa, oil palm and sugarcane produced (in 1000 tonnes on dry matter basis) across different regions. All values 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**

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

3.2.2. By-products from slaughterhouses

Globally, the largest quantity of residues produced annually was from cattle (16.5 million tonnes) followed by chicken (10.7 million tonnes) and pigs (6.2 million tonnes), but with wide variation among regions (Table 6). The largest quantity of by-products from cattle was recorded in South America (5.31 million tonnes) of which Brazil accounted for 77% of by-products produced in that region. This was followed by Northern America (4.59 million tonnes of which 94% was in USA) and Eastern Asia (0.99 million tonnes of which 84% was produced in China). The total annual production of by-products from poultry processing was largest in North America (6.0 million tonnes) of which over 99% was produced in the USA. This was followed by East Asia (0.91 million tonnes) of which China accounted for over 72% of the production in East Asia.

Table 6. Estimated total annual quantity of slaughterhouse by-products potentially produced (in 1000 tonnes on dry matter basis) across different regions. All values were estimated using FAOSTAT data (see 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

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

3.3.3. By-products from fisheries and aquaculture

The estimated annual quantity of by-products potentially produced from processing of selected fish species in aquaculture and capture fisheries are summarized in Table 6. Among the species grown in aquaculture, the largest quantity of by-products was produced by rainbow trout (over 0.08 million tonnes) across 91 countries (Table 7). The largest proportion was recorded in Southern Asia (predominantly in Iran and Tukey), followed by South America (mainly in Peru and Chile) and Northern Europe (mostly in Norway) (Table 7). Among the capture fisheries species, the largest quantity of by-products was produced from skipjack tuna harvest (0.14 million tonnes) followed by yellowfin tuna (0.08 million tonnes).

Table 7. Estimated total annual quantity of by-products potentially produced (in tonnes on dry matter basis) by selected fish species in aquaculture and capture fisheries across different regions. All values were 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**

3.3. Livestock manure

Globally, cattle, buffaloes and chicken produced the largest proportion of the potential annual

manure produced every year (Table 8). On dry matter basis, non-dairy cattle produce an estimated

2.23 billion tonnes (CL: 1.32–3.23), while dairy cattle produce about 0.82 billion tonnes (CL:

0.50–1.21) annually. The largest quantity of non-dairy cattle manure was produced in South

America (where Brazil accounts for 60%) followed by South Asia (where India accounts for 68%).

Annual production of dairy cattle manure was largest in South Asia (where India accounts for 68%).

The largest annual manure production by buffaloes occurs in East Asia (China accounts for 99%)

and South Asia (India accounts for 70%). The largest quantity of broiler chicken manure was

recorded in South-Eastern Asia, where Indonesia accounts for 76% of broiler chicken manure in

577   that region. The next largest production was recorded in South Asia where Pakistan and Iran

578   account for 42% and 37% of the regional production (Table 8).

579   **Table 8**. Estimated total amount of manure potentially produced annually (in 1000 tonnes on dry matter
580   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
	South America	598417	84428	3450	9312	79881	3305	580	17176
Asia	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
	Western Asia	29132	32374	1092	125	27461	1734	47	453
Europe	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
	Western Europe	52432	33624	19	8601	14392	1234	1467	578
Oceania	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

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

582

3.4. Wood residues

584   Globally, an estimated 0.23 billion tonnes (CL: 0.08−0.43) of wood residues are produced every

585   year (Table 9), but the largest production occurs in East Asia (China producing the highest)

586   followed by South America and North America where Brazil and USA have the highest production,

587   respectively. Annual wood residue production was highest in China (95.1 million tonnes) followed

588   by Brazil (18.8 million tonnes). The values presented in Table 8 are based on countries for which

589   data were available in FAOSTAT. Since data are not available for all countries in many regions, it

590   was not possible to calculate the residue production per country as a proportion of the total

591   production in the respective region. Countries in the Caribbean, Central Asia, Middle Africa,

592   Western Africa, Northern Africa and Southern Asia are poorly represented (Table 9).

593

594   **Table 9**. Estimated total annual wood residue potentially produced (in 1000 tonnes on dry matter basis)
595   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'Ivore
	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**	
	Lower 95% CL[†]	**79837**	
	Upper 95% CL[†]	**426061**	

596
597

4. Discussion

599   The preceding sections have presented indicative estimates of the quantities of agricultural residues

600   and by-products for selected crops and animals available in the OMD. Due to the lack of uniform

601   methodology and data across countries, it was not possible to accurately estimate the quantities of

602   residues produced by all crops and agro-processing activities. We are also keenly aware that the

603   values presented could either overestimate or underestimate the global residue production.

604   However, OMD is a living database that will be updated and enriched as new data and methods

605   become available to build a solid reference resource for industry, researchers and decision-makers

606   in soil health management, pollution risk reduction, bioenergy production and other sectors. The

607   OMD is envisaged to complement existing databases such as FAOSTAT, FishStat and organic

608   resource quality databases such as Phyllis. The OMD may be used for various purposes including

609   estimation of availability for soil amendments, animal feed, bioenergy and other agricultural

610   activities such as mushroom production. The use of agricultural and forestry residues and by-

611   products for soil amendment may be constrained by these competing uses (Duncan et al., 2016; Ji et

612   al., 2018). The following sections will discuss the production and competing uses of agricultural,

613   fisheries and forestry residues, and the opportunities and challenges for their use as soil amendment.

614

4.1. Crop residues

616   The estimates provided for the selected crops (Table 3) reveal that large quantities of crop residue

617   biomass are produced annually. However, there are large differences in the share of residues of the

618   different crops among countries and regions. For example, the largest total annual production of

619   maize residue was recorded in Northern America, whereas the largest wheat and rice residue

620   production was recorded in Southern Asia. Our estimates are based on uniform application of a

621   single equation for each crop across countries due to lack of country-specific conversion

622   coefficients. We are keenly aware that this can affect the accuracy of estimates in the database. The

623   use of country-specific harvest indices or equations could have provided more accurate data.

624   The competing uses of residues may vary among regions, countries and even farming systems

625   within countries. We were unable to disaggregate the total residue into the different categories due

626   to the lack of country-specific data on the proportion fed to animals, burnt or left on the ground.

627   According to estimates by Smerald et al. (2023), about 44% of cereal residues is left on field, 33%

628   is used for animal feed and bedding, 16% is used for other purposes and 6% is burnt globally. In

629   China, which is one of the largest producers of crop residues, 82.3% is currently collected and used

630   either as fertilizer (62.3 %), feed (16.0 %), energy (9.6 %), cultural substrate (0.8 %), or as a raw

631   materials (1.1 %) (Zhao et al., 2024). In many parts of the world crop residues are widely used as

632   soil amendments or as a mulch to protect the soil from erosion. Farmers also remove residues to

feed animals or use them as beddings. For example, about 16% of the collectible crop residues is used as animal bedding in Europe (Monforti et al., 2013). In the EU member states alone, around 28 million tonnes of crop residues are used for animal bedding annually (Scarlat et al., 2010). Crop residues are also used as fuel in industrial and domestic set-ups. For example, in rural areas in Africa and Asia, crop residues are used for cooking. There is also a growing interest in the use of crop residues for the generation of biofuels as alternatives to fossil fuels and industrial applications including textiles, natural fibres, polymers, biosorbents and reinforcement material in composites (Siqueira et al., 2022). However, country-specific data are virtually lacking to produce a database of the competing uses.

The estimated total annual crop residue produced by the top cereal and legume crops across the different regions indicate the high potential for their use in soil amendment and contribution to bioeconomy processes. Depending on the availability of technology for recovery, some of the crop residues produced may be used for recycling in bioenergy production and use as soil amendments. Raw crop residues such as straw can be incorporated into the soil or applied on the soil surface as a mulch, and this can reduce erosion, maintain soil moisture and add carbon and nutrients to the soil. A growing body of meta-analyses have provided compelling evidence that residue retention significantly increases crop yields, soil nutrient stocks, water use efficiency, carbon sequestration, microbial diversity and functionality (Shu et al., 2022; Wang et al., 2020).

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

659 two or three cropping rounds per year (Van Hung et al., 2020). In such systems, soil application of

660 residue poses challenges due to the insufficient time for decomposition of the straw, which hinders

661 crop establishment. This has led to an increase in open field burning of rice straw in some Asian

662 countries (Lin and Begho, 2022; Van Hung et al., 2020).

663   Of the residues produced annually, only a small fraction may be recovered because the

664 collection, storage and transportation of raw residues poses challenges for their use outside their

665 production area. One way to reduce the cost of transport and increase their use is to convert bulky

666 residues and by-products into briquettes, pellets, biochar or anaerobic digestate that can be more

667 easily handled and transported than the raw residues (Bora et al., 2020). In some regions, the short

668 time frame between two cropping seasons may not allow collection of the available residues (FAO,

669 2014; 2021). Even when collection is feasible, the cost of transportation may limit soil application

670 far from the farm where the residues were produced. This may be overcome by mechanized

671 collection, high-density compaction, briquetting, pelletizing or on-site processing (e.g., composting

672 or anaerobic digestion). High-density compaction can reduce the volume of crop residues thus

673 making it easier to store and transport over a long distance. For example, the volumetric weight of

674 mechanically compacted rice straw bales is 50–100% higher than that of loose straw. Briquetting

675 and pelletizing can further increase the volumetric weight of baled straw by up to 700% and reduce

676 transportation costs by more than 60% (Balingbing et al., 2020).

677   The quality of residues may play a critical role in the build-up of carbon and nutrients in the

678 soil (Cotrufo et al., 2013) against the backdrop of the importance of the soil ecosystem (Schmidt et

679 al., 2011). The carbon content of residues is about 30-50% (Table 1). The nitrogen content of

680 various cereal straws ranges between 0.3 and 2.8%, and only pulse straws are relatively nitrogen-

681 rich (Table 1). With low C:N ratios (Table 1), residues from legumes are likely to decompose more

682 rapidly than cereals. The phosphorus and potassium content of most residues is 0.05-0.3% and 0.2-

683 2%, respectively (Table 1). As such, crop residues represent a substantial store of carbon and

684 nutrients that can be used as inputs for soil amendment. A role of crop residue incorporation that

685 has remained less appreciated is their contribution to soil micronutrient stocks especially sulphur,

686 calcium, magnesium, zinc and silicon that are often not part of the recommended fertilizers. Where

687 straw is incorporated, reserves of soil nitrogen, phosphorus, potassium and silicon have also known

688 to be maintained at acceptable levels (Dobermann and Fairhurst, 2002).

689

690 **4.2. Agro-processing by-products**

691 Our estimates indicate that substantial quantities of by-products are produced every year, but with a

692 great deal of variability across regions. Unlike crop residues, most of the by-products are produced

693 in localized processing plants, which makes their collection more convenient. However, some of the

694 by-products may not be available for soil amendment as they have various other uses. For example,

695 husks of rice are mostly used as fuel in the rice mills (Petersen et al., 2015). Rice husk is also used

696 as an insulating material. In crops such as oil palm, cocoa and coffee, the processing also occurs in

697 a few countries where the commodities are grown on commercial scale.

698 Although oil palm is widely cultivated in plantations across the humid tropics of Asia, Africa

699 and the Americas, over 90% of the global palm oil production occurs in just five countries, namely,

700 Indonesia (58.8%), Malaysia (25.6%), Thailand (3.9%), Colombia (2.9%) and Nigeria (1.4%)

701 (Murph et al., 2021). Although the oil palm industry is one of the best sources of organic inputs for

702 agricultural use (Adu et al., 2022; Embrandiri et al., 2012), the residues may not be available for

703 direct soil application in areas far from processing plants. However, this can be circumvented

704 through conversion into compost or digestates, which are easier to handle and transport.

705 Our global estimate of sugarcane bagasse production (548.7 million tonnes is very closes to

706 the 540 million tonnes reported in Bezerra and Ragauskas (2016). Unlike other crop residues,

707 bagasse is not readily available for soil amendment. This is because much of the bagasse produced

708 is used for steam generation in sugar mills and the remainder is burnt as dry bagasse is known to be

709 a fire hazard. Bagasse consists roughly of 20–30% lignin, and 40–45% cellulose and 30–35%

710 hemicellulose, making it a promising feedstock for second-generation biofuel production (Bezerra

711 and Ragauskas, 2016; Petersen et al., 2015). In some countries bagasse is also used as a raw

712 material for the paper and board industry.

713   While slaughterhouse operations produce large quantities of by-products, some of are

714 processed by the rendering industry for conversion into animal feed, pet food, poultry meal and

715 animal fats (Mozhiarasi and Natarajan, 2022). There are challenges to the availability of by-

716 products from slaughterhouse and fish processing facilities for soil application. Different parts of

717 animal such as head, feet, fat, and blood can be used in a variety of ways, and therefore may not be

718 readily available for soil amendment. Some fish parts, especially viscera, deteriorate very rapidly

719 and therefore they require preserving as soon as possible after being produced. This is not always

720 possible due to inadequate processing facilities or limited volumes making recovery of the by-

721 products unprofitable. When fish are processed to fillets at sea, viscera, the head and frames are

722 often discarded since refrigeration facilities are used for the most valuable product (Olsen et al.,

723 2014).

724

725 **4.3. Livestock manure**

726 Our estimates in Table 7 show that large quantities of manure are produced annually albeit large

727 variability across regions. These estimates include both manure management systems and manure

728 left on pasture. Only a fifth of livestock manure produced is applied on cropland due to various

729 constraints. For example, much of the manure produced may not be available for application as soil

730 amendment on cropland because over 70% is directly deposited on pasture (FAO, 2018). Manure

731 applied to soil can be a significant source of macronutrients and micronutrients (FAO, 2018; Sileshi

732 et al., 2019). In addition, manure is a significant source of organic matter, which is a key

733 determinant of soil health (FAO, 2018). For example, globally manure applied to soil was estimated

734 to contribute 24 and 31 million tonnes of nitrogen per annum based on IPCC Tier 1 and Tier 2

735 approaches, respectively (FAO, 2018). According to van Dijk et al. (2016), manure application on

736 soil constitutes approximately 53% of the P and 33% of the N applied annually to agricultural land

737 in the EU27.

738   Even if manure is available in abundance, its application may be constrained by

739 environmental quality and economic considerations in some jurisdictions. For example, in the USA,

740 the Environmental Protection Agency regulation requires large animal feeding operations to meet

741 nutrient planning requirements for land application of manure. Similarly, according to the EU

742 Council Directive 91/676/EEC, the amount of livestock manure applied to land each year shall not

743 exceed 170 kg N per hectare. Legislation may also forbid manure application during certain periods

744 (e.g., in non-cropping seasons) or land that would otherwise lead to environmental impact through

745 run off or nutrient leaching (Loyon, 2018).

746   The bulky nature of manure limits the areas over which it can be economically applied.

747 According to Paudel et al. (2009), the economically optimal distances for dairy manure application

748 is 30 km for nitrogen and 15 km each for phosphorus and potassium to meet the recommended N,

749 P_2O_5 and K_2O needs on cropland. Conversion of manure into anaerobic digestate or compost can

750 circumvent the handling, storage and transportation costs of raw manure from intensive animal

751 production units. When efficiently managed and recycled within agricultural systems, livestock

752 manure represents a large source of plant nutrients that can reduce the need for synthetic fertilizer

753 inputs and reduce GHG emissions (FAO, 2018). Manure may be applied by injection, band

754 application, surface spreading or incorporation (Emmerling et al., 2020). Injection has been cited as

755 the best application method to reduce NH_3 emissions, while surface application using splash plates

756 has been banned in most European countries because of its strong impact on NH_3 emission

757 (Emmerling et al., 2020).

758

759 **4.4. Wood residues**

760 Wood residues are obviously underestimated for many regions because data were unavailable for

761 some countries. Among the countries for which data exist, annual wood residue production was

762 highest in China and Brazil, representing 42% and 8.3% of the annual global wood residue

763 production. Wood log production in Brazil generates about 50.8 million m^3 of lignocellulosic

764 residue yearly (Domingues et al., 2017). Assuming a wood density of ~450 kg m^3 this value is

765 approximately 22.9 million tonnes, which is slightly higher than 18.8 million tonnes in our

766 database. The competing uses of wood residues include use as woodfuel for domestic purposes

767 (Flammini et al., 2022), bioenergy generation (Karan and Hamelin, 2020) and as raw materials for

768 the manufacture of agglomerated products such as pulp, particle board and fibreboard (FAO,

769 2022f). Although wood residues could be potentially used for soil amendment after processing (e.g.,

770 wood-ash, biochar, compost, etc.), the proportion actually available may be small due to their

771 various competing uses. Agroforestry trees and plantation crops such as coconut, oil palms, and

772 rubber generate considerable amounts of woody and leafy biomass from pruning and lopping. A

773 large proportion of such residues can be used for soil amendment directly or after processing into

774 compost or biochar (Bluhm and Lehmann, 2023). However, data were not readily available for

775 these residues, and therefore it was not possible to collate their quantities in the OMD.

776

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

778 One of the key limitations of this work is the lack of country-specific data on the quantities of the

779 some categories of residues such as crop residues and manure. Country-specific conversion factors

780 or equations are also lacking to convert production statistics to residue data. As a result we were

781 forced to use a single conversion factor or a single equation in some cases. A second limitation of

782 this work is our inability to provide global estimate of all residues from agriculture, fisheries and

783 forestry. The effort to compile estimates of all residues and by-products was hampered by the lack

784 of methods for conversion of primary products to residues and industry standards for collection and

785 aggregation of such data. For example, we did not included the quantities of residues produced by

786 minor crops, fruit trees and other trees in agroforestry and forestry. A third limitation of this work is

787 that were unable to account for situations where products are processed in a different country than

788   their origin as this would entail additional data on export and import. This could be considered an

789   important future endeavour in the development new versions of the OMD.

790   The OMD also does not contain the quantities of by-products such as biochar, compost and

791   digestate produced in each country due to lack of data on their production. By-products of

792   secondary processing that occurs in the breweries and beverage industry could also not be compiled

793   due to lack of mechanisms to capture them at the country levels. By-products from capture fisheries

794   were estimated only for a few species because conversion factors were unavailable for the majority

795   of species. Even for those species where conversion factors were available, residues from capture

796   fisheries were probably underestimated by a large margin because recovery of inedible parts is

797   challenging. This is because fish are processed at sea, and non-edible parts may be discarded in the

798   sea (Olsen et al., 2014). Commercial fish products are often directly processed on-board vessels

799   and, by the time they are landed, the fish have been frozen, gutted, headed, and/or processed,

800   leading to a considerable change from their original weight. This leaves a great deal of uncertainty

801   about estimation of fisheries by-products. We were also unable to provide uncertainties associated

802   with estimates of the quantities presented at national or sub-national level due to the lack of data.

803   Therefore, we strongly recommend investment in the inventory of agricultural, fisheries and

804   forestry residues, by-products and wastes at the national and sub-national levels for use in a circular

805   bio-economy.

806   This work only provides an inventory of the various residues at the country level, which is

807   valuable in its own right. However, further work needs to be done to produce a global map of

808   carbon and nutrients from residues at much greater spatial distribution and finer resolution than

809   individual countries to inform policy and good practice for more efficient allocation of biomass

810   resources. There is also an urgent need for documenting the alternative and competing uses of the

811   various categories of residues estimation of the share of different uses of each residue and unused or

812   wasted residues at the national and local levels. This requires further work and deemed outside the

813   scope of this publication.

814   Due to lack of basic data, this work was unable to determine the proportion of the residues in

815   each category that is actually available for use as soil amendment. Even where data were available,

816   legislative and regulatory issues may limit their use as soil amendments. For example,

817   environmental concerns of pollution by antibiotics, heavy metals and pathogens have led to

818   regulations on direct spread of manure on land (Font-Palma, 2019). Strict regulations such as those

819   under the EU Nitrates Directive 91/676/EEC (EEC, 1991) mean that only a small proportion of the

820   total volume of manure produced can be used for soil amendment. It is also forbidden to apply

821   manure or anaerobic digestate at particular times in the year or on certain types of land (Loyon,

822   2018). In some jurisdictions, organic matter that has been designated as waste may be subject to

823   regulatory restrictions on how it can subsequently be used or managed (Loyon, 2018). In this

824   analysis, it was not possible to evaluate the extent to which national policies and regulatory

825   frameworks governing the classification of organic matter streams as wastes or by-products, and

826   waste management can provide incentives or not to the use of organic inputs for soil amendment.

827   Legislation banning residue burning and incentives for farmers to adopt good agricultural practices

828   can also incentivise appropriate use of agricultural residues. For example, EU Regulation No

829   1307/2013 has established rules for direct payments to farmers under support schemes within the

830   framework of the common agricultural policy. To receive full payments, farmers in the member

831   states have to comply with statutory management requirements and standards for good agricultural

832   and environmental conditions, and the requirements of 'greening' (Heyl et al., 2021). Quantitative

833   targets are used to incentivize the implementation of agricultural practices that increase SOC stocks

834   (Bruni et al., 2022). For example, the EU Mission Board for Soil Health and Food proposed a series

835   of quantitative targets for soils to become healthier. Among them, the current SOC losses of about

836   0.5% per year in the 20 cm soil depth of croplands should be reversed to an increase of 0.1–0.4%

837   per year by 2030 (Bruni et al., 2022). Such targets and related regulations will have implications for

838   how and where agricultural residues can be used for soil amendment.

839 Transport costs may also hinder the use of the excess volume produced in one region in other

840 regions. In some regions, anaerobic digestate is produced in excess of its agricultural assimilation

841 potential (Torrijos, 2016). For example, in the EU digestate production reached 56 million tonnes

842 per annum by 2010, of which 80% could be recycled back into agriculture (Kizito et al., 2019).

843 Similarly, in China the annual digestate production is approximately 2.3 billion tonnes of which less

844 than 70% is recycled back to agriculture due to land limitations (Kizito et al., 2019). These

845 observations highlight the need to explore opportunities for use of residues and by-products outside

846 the country where they are produced.

847

848 **Data availability:** The OMD data is available at: https://doi.org/10.5281/zenodo.10450921

849 (Sileshi et al., 2024).

850

851 **6. Conclusions**

852 This work has provided typologies, definitions and quantities of the various agricultural residues

853 and by-products, which can be useful for the inventory and estimation of the various residue

854 streams potentially available for recycling in agriculture, bioenergy and other sectors. The OMD is

855 the first of its kind to consolidate biomass estimates of residues and by-products from agriculture,

856 fisheries, forestry and allied industries globally. The OMD will be continuously updated as new

857 production data are published in FAOSTAT and will be publicly available for use by different

858 decision-makers. It is hoped to contribute to the Better Production and Better Environment

859 dimensions of FAO's Strategic Framework 2022-2031 supporting the 2030 Agenda. The OMD is

860 also expected to contribute to evidence-based policies and actions in support of the transition

861 towards a circular economy, and more sustainable agriculture and food systems. Currently, the

862 estimates of crop residues and manure in OMD are available only at the national level based on a

863 single equation applied uniformly due to the lack of country-specific conversion factors. Therefore,

864 finer scale data and country-specific conversion factors and/or equations are urgently needed for

spatial targeting of residues and by-products for various applications. Detailed site-specific

inventory of various categories of residues and their local uses are highly recommended. An

inventory of the competing uses and fate of the various residues and wastes is also urgently needed

in each country.

Authors' contributions

EB, GWS, FNT conceptualized and designed the study. GWS, JL developed the methodology and

GWS conducted data curation and formal analysis. GWS, EB wrote and edited the manuscript,

while JL, FNT reviewed and edited the manuscript. EB funding acquisition. All authors have read

and approved the final version of the manuscript.

Competing interests

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

Disclaimer

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