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1 Quantification of indirect waste generation and
2 treatment arising from Australian household
3 consumption: a waste input-output analysis

4
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27 Abstract

28

29 Waste input-output (WIO) model is a suitable method to explore the nexus between economic
30 activities and waste management. Contemporary research that typically explores this nexus follows
31 two main aspects: either they consider Final demand as a whole, or they identify the nexus between
32 households, with different types of socio-demographic indicators and household waste generation.
33 However, it is complex to apply the WIO model from the perspective of household consumption— a
34 major component of Final demand — because of a lack of economic and environmental data related
35 to household consumption. This paper proposes a new perspective, applying the WIO model to
36 assess the nexus between different patterns of household consumption and indirect waste
37 generation and treatment. This novelty is to combine macro- and micro- economic and
38 environmental data related to Australian industrial sectors, different patterns of household
39 consumption (Mosaic data), and direct waste generation into the WIO model for exploring this nexus
40 in two scenarios. Results indicate that the total amount of indirect waste generation caused by B05
41 (couples without children who spend the majority of their time at the office) are 99.24 kg more than
42 that of D16 (couples without children who are retired and stay at home) for scenario I. The
43 correlation coefficients for differences of output of economy and indirect waste generation between
44 B05 and D16 are 0.9796 and 0.9773 in scenarios I and II, respectively. Sensitivity analysis indicates
45 the change of the amount of direct waste generation in a reasonable range cannot dramatically
46 affect the major economic activities and waste generation. This research suggests a different
47 perspective of household consumption to estimate indirect waste generation through a WIO model
48 to provide more reliable information for waste management in the supply chain.

49

50 **Keywords:** waste input-output, household consumption, Australian economy, waste footprint

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56 1. Introduction

57

58 Humans consume an increasing variety of goods and services produced by industrial sectors, which
59 cause direct and indirect waste generation. Humans are the principal factor for driving production,
60 consumption, and subsequently, the resulting waste generation (Karak et al. 2012). Direct waste
61 generation of household consumption refers to the waste generated from household members at
62 home (Ponis et al. 2017). Indirect waste generation in this research indicates that the waste
63 generated in the supply chain of the economic system caused by household consumption. With the
64 sharp growth of population, the amount of waste generation is forecasted to increase by about 70%
65 globally in 2050 (The World Bank 2018).

66 Developed countries, such as United States, United Kingdom (UK), and Australia generate more
67 waste per capita per day than developing countries (such as Bangladesh, Vietnam, and Malaysia)
68 (Mmerekki et al. 2016). For example, the average amount of waste per capita per day in Australia
69 (7.40 kilograms) (Department of the Environmental and Energy 2017) is about 10 times more than
70 that the global average (0.74 kilograms) (The World Bank 2018) in 2016. The amount of Australian
71 waste generation is forecasted to increase by approximately 60% by 2050 (Big Australia 2018).
72 Developed countries have higher rates of recycling than developing countries. For instance, 60%
73 waste generated in Australia was recycled in 2014–15 (Department of the Environmental and Energy
74 2017) while only 22% of the total waste generated in Malaysia have been estimated to be recycled
75 (Moh et al. 2014). There are considerable variations and complexities in waste generation due to
76 different patterns of household consumption, the industrialized degree of countries, and the ability
77 of treating waste.

78 One of the major global waste reduction goals is Sustainable Development Goal (SDG) 12, which
79 seeks to substantially reduce waste generation through prevention, reduction, recycling and reuse
80 (SDG 12.5), and halves per capita global food waste at the retail and consumer levels (SDG 12.3) by
81 2030 (United Nations Statistics Division 2018). In order to achieve SDG 12, substantially reducing
82 waste generation, and comprehending the complexity of waste management, there must be a
83 systematic analysis of how waste generation and treatment interact with human consumption
84 within an economic system on two fronts. First, how different patterns of human consumption
85 activities affect waste generation and treatment should be analysed. Second, the nexus between the
86 economy and waste generation must be assessed.

87 Studies regarding how/where waste is generated in the supply chain, and how waste is treated by
88 different waste treatment methods have been proliferated. One popular research framework for
89 displaying and analysing the complexity of waste production and treatment has been input-output
90 (IO) modelling: a type of quantitative macroeconomic accounting that represents the
91 interdependencies between different branches of a national economy or different regional
92 economies. A short summary of IO modelling and waste follows: Joosten et al. (2000) used national
93 supply–use tables to explore the nexus between plastic products and intermediate sectors in the
94 Netherlands in 1990. Kagawa et al. (2004) delivered a simple multiregional IO model for waste
95 analysis to estimate intraregional and interregional effects of industrial wastes caused by regional
96 final consumptions. They have provided the analysis for the nexus between economic activities and
97 waste management, but failed to account for detail analysis for patterns of consumptions and waste
98 types. Nakamura and Kondo (2002) have linked waste types with treatment methods via the
99 development of the waste input-output (WIO) model, which allows different types of waste
100 treatment methods to “treat” or “dispose” of multiple types of waste. The WIO model has been
101 developed further into a waste supply-use tables (WSUTs) that allows this complexity of treatment
102 and waste flow to be seen in a single table (Lenzen and Reynolds 2014). The WSUT framework was
103 used to demonstrate how Australian waste generation is affected by the intermediate sectors and
104 waste treatment sectors (Reynolds et al. 2014). Based on the WSUTs, a multi-regional WSUT was
105 developed to analyse the indicators of waste generation, such as the waste footprint and sectoral
106 waste production intensity (Fry et al. 2015). Saleem et al. (2016) developed the first version of
107 the UK WIO model table to analyse direct and indirect waste arising across the supply chain. He et al.
108 (2017) compiled an Australian WIO table based on data from the Australian Bureau of Statistics
109 (ABS). In terms of WIO model, the nexus between the economic system and waste management has
110 been analysed to offer effective information (e.g. waste footprint and sectoral waste production
111 intensity) for environmental policy-makers. Alabi et al. (2017) applied IO multiplier methods to
112 develop an understanding of demand drivers of physical waste. Zeller et al. (2018) developed
113 regional waste supply and use tables in terms of regional waste statistics and national input-output
114 tables. These were used to quantify waste generation from households. Nakamura et al. (2018)
115 extended function of the WIO model from a static model to a dynamic model, which covers the issue
116 of quality in recycling that involves mixing, dissipation, and contamination. He et al. (2018)
117 investigated the effect of the Household sector as an ‘endogenous’ factor on waste generation and
118 treatment based on the environmentally-extend input-output model. Liao et al. (2015) have
119 analysed the effect of household consumption on waste generation. Ruiz-Peñalver et al. (2019) have
120 estimated total waste generation throughout the supply chain in Spain. These studies adjusted the

121 basic structure of IO table to explore the nexus between economic activities and waste generation and
122 treatment based on the Final demand (Final demand being made up of consumption by households
123 and government as well as capital formation, inventory and exports). However, there remains a lack
124 of detailed analysis on 1) the effect of changing components within Final demand (ie household
125 consumption), or 2) the socio-demographic sub-population effects of consumption on waste
126 generation. Therefore, it is necessary to conduct detailed analysis from the perspective of different
127 socio-demographic sub-population types to identify what effects the different patterns of
128 consumption have on waste generation and treatment in the economic system.

129

130 Consumption is the major driver for waste generation (Wilson 2007). Consumption can be
131 disaggregated into different types via different socio-demographic characteristics, such as income,
132 education, and household size. Some studies explored the nexus between household consumption
133 and waste generation (see (Parfitt et al., 2010, Song et al., 2015)), or waste composition (see
134 (Daskalopoulos et al., 1998, Edjabou et al., 2015)). How different demographic indicators of
135 consumption, such as income (Johnstone and Labonne 2004, Bandara et al., 2007, Aparcana 2017),
136 household size (Dennison et al., 1996, Triguero et al., 2016), and education (Barr 2007, Benítez et al.,
137 2008, Han et al., 2018) affected waste generation has been illustrated. Although the above-
138 mentioned studies analyse the direct effect of the household consumption on waste generation,
139 little attention has previously been paid to the effect of household consumption on indirect waste
140 generation and treatment in the economy. The analysis of indirect waste generation in the supply
141 chain can give a description of how human consumption patterns affect waste generation and
142 treatment, which benefits decision-making for waste management. This lack of publications in this
143 area is mainly due to the limitation of supply chain level waste data – rather than any conceptual or
144 mathematical restriction. In addition, it is difficult to compare the results of how the different
145 patterns of household consumption affect indirect waste generation and treatment across the
146 regions and time frames because of inconsistencies of the scope and the substantial gaps in the
147 available information (Thyberg et al., 2015, Reutter et al., 2017).

148

149 This paper aims at filling this knowledge gap through providing a novel perspective and case study to
150 analyse the effects of different patterns of household consumption on the indirect waste generation
151 and treatment in Australia, along with two novel variants to overcome limitations shown in the
152 literature: (i) a version of Mosaic data describing the information of different patterns of
153 consumption categorised by different socio-demographic data for the household; and (ii) on-site
154 collected data for household waste generation and treatment corresponding to different patterns of

155 consumption to refine and compile the WIO table. This linking of Mosaic data and on-site waste
156 collection data to a WIO table is a novel and new contribution to the literature.

157

158 The paper is structured as follows: the Method section gives information on the method of WIO
159 model, data sources, sensitivity analysis, and the design of different scenarios. The Results section
160 shows the effects of different patterns of household consumption on indirect waste generation and
161 treatment and the comparative analysis between different scenarios with the sensitivity analysis.
162 The Discussion section indicates the major findings based on different patterns of household
163 consumption and scenarios with the discussed sensitivity analysis. The Conclusions section displays
164 the novelty of the research, the advantages and disadvantages of the comparative analysis, and
165 future research.

166

167 2. Method

168

169 2.1 Method of the WIO model

170

171 The basic method and notation of the WIO model was introduced in Nakamura and Kondo (2002).

172 The WIO model in balanced form from He et al. (2017) is written as

$$\begin{pmatrix} K_{I,I} & K_{I,II} \\ PG_{,I} & PG_{,II} \end{pmatrix} + \begin{pmatrix} X_{I,F} \\ PW_{,F} \end{pmatrix} = \begin{pmatrix} x_I \\ x_{II} \end{pmatrix} \quad (1)$$

173 where $K_{I,I} \in \mathbb{R}^{N^I \times N^I}$ represents intermediate sectors' matrix for N^I goods and service-producing
174 sectors, the components of $K_{I,II} \in \mathbb{R}^{N^I \times N^{II}}$ mean the monetary inputs from per intermediate industry
175 into N^{II} waste treatment sectors, P is an $N^{II} \times N^w$ nonnegative matrix for N^w waste types, and the
176 p_{ij} in the matrix represents the proportion of waste j treated by waste treatment method i , $G_{,I}$ is
177 defined as an $N^w \times N^I$ matrix for the category of waste generated by intermediate sectors, $G_{,II}$
178 represents an $N^w \times N^{II}$ matrix that the waste is generated by N^{II} waste treatment sectors. A Final
179 demand matrix for N^I goods and service-producing sectors is defined as $X_{I,F}$ for N^F sectors, and $W_{,F}$
180 is the waste generated by Final demand. $x_I \in \mathbb{R}^{N^I \times 1}$ refers to a gross output vector for N^I goods and
181 service-producing sectors, and $x_{II} \in \mathbb{R}^{N^{II} \times 1}$ presents the total amount of waste to be treated by N^{II}
182 waste treatment sectors.

183 The coefficient matrix of WIO model can be expressed

$$\begin{pmatrix} A_{I,I} & A_{I,II} \\ B_{I,I} & B_{II,II} \end{pmatrix} \begin{pmatrix} X_I \\ X_{II} \end{pmatrix} + \begin{pmatrix} X_{I,F} \\ PW_{,F} \end{pmatrix} = \begin{pmatrix} X_I \\ X_{II} \end{pmatrix} \quad (2)$$

184 where the research defines input coefficients matrices $A_{I,I} = K_{I,I} \hat{x}_I^{-1}$ (million \$AUD/million \$AUD),
 185 $A_{I,II} = K_{I,II} \hat{x}_{II}^{-1}$ (million \$AUD/ tonne), $B_{I,I} = PG_{,I} \hat{x}_I^{-1}$ (tonne/million \$AUD), and $B_{II,II} = PG_{,II} \hat{x}_{II}^{-1}$
 186 (tonne/tonne), where the “hat” over a vector x denotes a diagonal matrix with the elements of the

187 vector along the main diagonal. For instance, if $x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$, then $\hat{x} = \begin{bmatrix} x_1 & 0 & 0 \\ 0 & x_2 & 0 \\ 0 & 0 & x_3 \end{bmatrix}$.

188 The solution of Equation (2) is given by

$$\begin{pmatrix} X_I \\ X_{II} \end{pmatrix} = \left(I - \begin{pmatrix} A_{I,I} & A_{I,II} \\ B_{I,I} & B_{II,II} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{I,F} \\ PW_{,F} \end{pmatrix} \quad (3)$$

189 The research considers household consumption (HC) as the Final demand ($X_{I,F}$ (million \$AUD)) in the
 190 WIO model. Data collection and aggregation of household consumption and its direct waste

191 generation and treatment $\begin{pmatrix} X_{I,F} \\ PW_{,F} \end{pmatrix}$ will be discussed in Section 2.2. Then, the total output will be

192 calculated in terms of Equation (3). Finally, the input matrix by industrial sectors of the WIO model

193 $\begin{pmatrix} K_{I,I} & K_{I,II} \\ PG_{,I} & PG_{,II} \end{pmatrix}$ can be obtained from Equation (4). The process of calculation is written as:

$$\begin{pmatrix} K_{I,I} & K_{I,II} \\ PG_{,I} & PG_{,II} \end{pmatrix} = \begin{pmatrix} A_{I,I} & A_{I,II} \\ B_{I,I} & B_{II,II} \end{pmatrix} \hat{x}^{-1} \quad (4)$$

195 2.2 Data sources

196

197 The Australian WIO tables in 2009–2010 and 2010–11 can be obtained in the research of He et al.

198 (2017), which are illustrated in Tables A.1 and A. 2, available in the supplementary file. To

199 summarise, the model is a 1 region, 8 intermediate sector model, that is based on domestic

200 technology consumption. This section describes the data collection regarding household

201 consumption ($X_{I,F}$) and direct waste generation by household consumption ($PW_{,F}$). Two types of

202 data source were employed for obtaining $X_{I,F}$ and $PW_{,F}$:

203 (a) The household consumption ($X_{I,F}$) were derived from the Mosaic Index of Mosaic data

204 (Nicholas 2016). Australian households are categorised into 13 Mosaic Groups and 49

205 Mosaic Types according to a series of socio-demographic variables, such as annual income,

206 education, and employment status. The Mosaic data contains information about weekly
207 household consumption on goods and services (e.g. Fish and seafood and Bedroom furniture
208 repair) for different Mosaic groups and Mosaic types. Each Mosaic Group includes three,
209 four, or five Mosaic Types. These Mosaic Types are defined by the Grand index including 398
210 variables according to the three following categories: (1) Who We Are, (2) Where We Live,
211 and (3) What We Do (Nicholas 2016). D16 refers to couples without children who are retired
212 and stay at home while B05 refers to couples without children who spend the majority of
213 their time at the office. In Australia, these categories of Mosaic types D16 and B05 have
214 accounted for an important proportion representing about 38% of all Australian families
215 (ABS 2017) in the 2016 Census. There is a similar proportion for all Finnish households in
216 2009 with 28% for couples without children (Katajajuuri et al. 2014). The proportion of these
217 two Mosaic categories are expected to grow to more than 40% of the Australian families by
218 2036 (ABS 2015).

219 (b) The amounts of waste generation ($PW_{,F}$) of different types of Australian households were
220 collected from an on-site experiment in the Lochiel Park, which that has recently been
221 completed with approximately 110 homes in the north-east of Adelaide (Land Management
222 Corporation, South Australian Government 2008) and is a living laboratory of CRC Low
223 Carbon Living. The process of collecting data regarding $PW_{,F}$ is described below. First, on-
224 site survey about the amount of waste generated in eight households at Lochiel Park Green
225 Village in South Australia has been conducted to collect data from households' waste bins
226 (Ethics Approval, Application ID: 0000032810). In these eight households, seven of them
227 belonged to D16 while one of them belonged to B05 of Mosaic types. The classifications of
228 these eight households are based on the file of CRC Study Zone SA1 (Nicholas 2016). The
229 research weighed these households' bins every week for a total of 14 times from December
230 2nd 2015 to March 2nd 2016 by using an instrument marked in standard units. The three bin
231 Kerbside Waste Collection service at Lochiel Park indicates the function of the blue bin for
232 general waste, the yellow bin for recyclables, and the green bin for green organics
233 (Campbelltown City Council 2017). The municipal solid waste collected from these
234 households' bins are considered as the direct waste generation, which excludes bulky waste,
235 Waste Electrical and Electronic Equipment recycling waste, and construction waste.
236 Corresponding to the waste treatment sectors (the Landfill sector and the Recovery sector
237 (resource recovery)) in the Australian WIO table, the research considered that the amount of
238 waste in the blue bin were treated by the Landfill sector and that in the yellow and green
239 bins was treated by the Recovery sector. Due to data limitations, it is not possible to

240 distinguish between energy recovery and material recovery (material recycling). The
 241 amounts of waste ($PW_{I,F}$) generated by D16 and B05 and treated by the Landfill sector and
 242 the Recovery sector are shown in Tables 1 and 2, respectively. The household consumption
 243 per week on 755 types of goods and services are shown in the sheet of DollarUnique of HES
 244 Mosaic Index (Nicholas 2016). These 755 types of goods and services were aggregated into 8
 245 types of goods and services ($X_{I,F}$) corresponding to the number of intermediate sectors in
 246 the Australian WIO table, which are shown in Table 3. The data of $X_{I,F}$ and $PW_{I,F}$ were
 247 multiplied by 52 to obtain the annual household consumption and waste generation and
 248 treatment because the period of data of $X_{I,F}$ and $PW_{I,F}$ was weekly.

249 The exact composition of the waste was not recorded by the survey, only the bin destination
 250 (recycling or landfill). Though we do not have individual waste composition analysis, we provide
 251 supplemental data of South Australian and Adelaide population level municipal waste compositional
 252 analysis.

253 The source of the waste data the wider economy activities was sourced from He et al. (2017), which
 254 was based on the Australian Bureau of Statistics waste accounts (2009–2010 and 2010–2011), (ABS
 255 2013, 2014). The scope of waste from economic activities that is covered by Paper & Cardboard,
 256 Glass, Plastics, Metals, Organics (e), Masonry, Electrical & Electronic, Solid Hazardous Waste, Leather
 257 & Textiles, Tyres & Other Rubber, Timber & Wood Products, and Inseparable/Unknown. These waste
 258 accounts were cross checked with the previous estimates of Reynolds et al (2015a). Both included
 259 estimates of household waste. these were used to validate the results of our fieldwork.

260 **Table 1** The average amount of waste per week for D16 (couples without children who are retired and stay at
 261 home).

Address	Mosaic Type	The amount of waste landfilled (kg)	The amount of waste recycled (kg)
1	D16	2.97	7.63
2	D16	9.04	5.43
3	D16	6.06	18.39
4	D16	2.74	5.14
5	D16	5.92	8.54
6	D16	4.82	7.12
7	D16	8.01	7.71
Average	D16	5.77	8.60
Total (52 weeks)	D16	300.04	447.2

262

263 **Table 2** The average amount of waste per week for B05 (couples without children who spend the majority of
 264 their time at the office).

Address	Mosaic Type	The amount of waste landfilled (kg)	The amount of waste recycled (kg)
8	B05	3.83	7.85
Total (52 weeks)	B05	199.16	408.20

265

266 **Table 3** Aggregated household consumption per week on intermediate sectors.

Mosaic types	Ag	Mi	Ma	EGW	Co	Pa	AOI	WMS	Total
(\$AUD)									
D16	59.21	0	533.61	91.23	0	18.43	674.01	0.54	1377.03
B05	54.65	0	533.49	79.85	0	23.93	807.48	0.74	1500.14

267 Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water = EGW; Waste
 268 management services = WMS; Construction = Co; Public administration = Pa; All other industry = AOI.

269

270 2.3 Method of the sensitivity analysis

271

272 The sensitivity analysis is a technique of assessing how the uncertainty in the output of a model can
 273 be apportioned to different sources of uncertainty in the model input (Doubilet et al. 1985, Saltelli
 274 2002, Hamby. 1994). Sensitivity analysis has been widely applied into IO model to identify the
 275 uncertainty of the model output. As one of the major methods for sensitivity analysis, Monte Carlo
 276 method has been used for the assessment of uncertainty relating to the level of aggregation (Bullard
 277 and Sebald 1988), total CO₂ emission intensities (Hondo et al. 2002), multi-regional IO model to
 278 convert currencies (Lenzen et al. 2010), impacts of the model on eco-efficiency assessment (Egilmez
 279 et al. 2016), and technical waste and primary input coefficients (Yazan et al. 2016). Sensitivity
 280 analysis has also applied to other environmental models. Clavreul et al. (2012) developed a general
 281 method with a sequence of four steps for quantitative uncertainty assessment of life cycle analysis
 282 (LCA) of waste management systems. Salemdeeb et al. (2017) applied the similar method to conduct
 283 sensitivity analysis for the parameter values in the hybrid LCA approach. Due to the limitations of
 284 household waste, this section conducts a sensitivity analysis to determine how the amount of
 285 household waste (HW) collected on-site impacts the major variables in the WIO tables under a given
 286 set of assumptions.

287 The first step is to generate a random sample of the amount of HW based on the sample which have
 288 been collected on-site. The research first calculated the mean and standard deviation of the amount
 289 of HW and then followed the method of Pollard (1979) to calculate the adjusted means and
 290 deviations using a truncated normal distribution using the iterative Equations 5, 6, 7, and 8. The
 291 truncated normal distribution is used as the amount of waste cannot be negative, and the authors
 292 have assumed the maximum amount of waste to be the largest amount of on-site HW. The suffix n
 293 denotes the nth approximation to the maximum likelihood estimate, the B and C are the maximum
 294 and minimum numbers of the collected sample, and the symbols ϕ and Φ refer to the ordinate and
 295 cumulative area of the unit normal curve, \bar{X} is the average of the collected data, S is the standard
 296 deviation of the collected data. We found that after 5 iterations, stable estimates of the population
 297 mean and standard deviation, μ_n and σ_n , were reached:

$$298 \quad \alpha_n = (B - \mu_n)/\sigma_n \quad (5)$$

$$299 \quad \beta_n = (C - \mu_n)/\sigma_n \quad (6)$$

$$300 \quad \mu_{n+1} = \bar{X} + \sigma_n(\phi(\beta_n) - \phi(\alpha_n))/(\Phi(\beta_n) - \Phi(\alpha_n)) \quad (7)$$

$$301 \quad \sigma_{n+1}^2 = S^2 + (\bar{X} - \mu_{n+1}) + \sigma_n^2(\beta_n\phi(\beta_n) - \alpha_n\phi(\alpha_n))/(\Phi(\beta_n) - \Phi(\alpha_n)) \quad (8)$$

302 The second step is to apply the stable μ_n and σ_n to obtain a random sample of the amount of HW
 303 and input the sample into the WIO model to obtain the major indicators for waste generation and
 304 treatment. This research chose 10 values of the sample as the amount of HW for sensitivity analysis.
 305 This research also applies the same method to analyse 15 variables. It kept the variables of the
 306 column of the Household sector in the WIO table constant and input these 10 values of the amount
 307 of HW to obtain the corresponding indicators, such as the most inputs from the All other industry
 308 (AOI) sector and the most amount of waste generated in the Manufacturing sector. The last step is
 309 to calculate the coefficient of variation of the values of HW and indicators as well as identify
 310 whether the accuracy of indicators is affected by the uncertainty of the values of HW or not.

311

312 2.4 Design of different scenarios

313

314 Due to the different periods of data sources, such as $X_{I,F}$ in 2013, $PW_{,F}$ in 2015–16, and Australian
 315 WIO tables in 2009–10 and 2010–11, the research built two comparative scenarios. The comparative
 316 analysis based on these two scenarios was conducted for illustrating the differences of indirect

317 waste generation caused by household consumption of B05 and D16. The main reason for
318 conducting these two scenarios was to assess the effects of different years' economic situations on
319 indirect waste generation and treatment. The two scenarios are:

320 1) Scenario I – the year of input coefficient and Leontief matrix is 2009–10, the year $X_{I,F}$ is
321 2013, and $PW_{,F}$ is 2015–16.

322 2) Scenario II – the year of input coefficient and Leontief matrix is 2010–11, the year $X_{I,F}$ is
323 2013, and $PW_{,F}$ is 2015–16.

324

325 3. Results

326

327 3.1 Waste footprint (Indirect) of two scenarios

328

329 This section presents waste footprints for household consumption (D16 & B05) with the focus on the
330 share that is indirect generated in each industrial sector. Waste 'footprint' includes the waste people
331 dispose of directly (direct), plus all the waste produced upstream (indirect) during the production of
332 goods and services to satisfy human demand (Fry et al. 2015).

333 The (indirect) waste footprint caused by the household consumption of D16 (couples without
334 children who are retired and stay at home) in Scenario I is shown in Figure 1. From the left to right,
335 the diagram shows the amount of household consumption by D16, the amount of indirect waste
336 generation in industrial sectors, and finally the amount of waste treated by waste treatment sectors.
337 The amount of household consumption (left) is calculated by summarising the products and services
338 of D16 consumption by retrieving the $X_{I,F}$. The amount of indirect waste generation in industrial
339 sectors (middle) are found by retrieving the $PG_{,I}$. The amount of waste treated by the Landfill and
340 Recovery sectors (right) are found by retrieving the $PG_{,I}$ and $PG_{,II}$. In the supplementary appendix,
341 Figures 2, 3, and 4 have the similar expressions for D16 in scenario II, B05 (couples without children
342 who spend the majority of their time at the office) in scenarios I and II, respectively. In summary, the
343 analysis of waste generation based on a WIO model from 2010 instead of 2009 results in a reduction
344 of indirect waste generation of around 8%.

345

346 The amount of direct waste generation for D16 (747.24 kg) and B05 (607.36 kg) in Tables 1 and 2
347 are less than that of indirect waste generation for D16 (scenario I: 2129.90 kg and scenario II:

348 1960.76 kg) and B05 (scenario I: 2230.14 kg and scenario II: 2046.23 kg). Each industrial sector
349 generates indirect waste in scenario I more than that in Scenario II, except for the Mining sector. For
350 example, the most amount of indirect waste caused by household consumption of D16 are
351 generated from the Manufacturing sector in scenarios I (1033.81 kg) and II (1026.26 kg). As for waste
352 treatment methods, the amount of indirect waste (1148.43 kg) treated by the Landfill sector is
353 greater than that (981.47 kg) treated by the Recovery sector in scenario I. Scenario II shows the
354 similar situation with the Landfill sector treating 1049.55 kg and the Recovery sector treating 911.21
355 kg indirect waste. The exact composition of the waste in each stream/treatment method was not
356 analysed due to lack of data.

357

358 The B05 has generated more indirect waste than the D16 in scenarios I (B05: 2229.14 kg and D16:
359 2129.90 kg) and II (B05: 2044.23 kg and D16: 1960.76 kg) with more household consumption (B05:
360 \$AUD 77,968.80 and D16: \$AUD 71577.48). The indirect waste generation and treatment caused by
361 the household consumption of B05 has similar analysis with that by that of D16, shown in Figures 3
362 and 4.

363

364 3.2 Comparative analysis of different types of households on 365 indirect waste generation in Australian economy with 366 different scenarios

367

368 This section compares indirect waste generated in each industrial sector, which are caused by the
369 household consumption of B05 and D16 in different scenarios. The differences of indirect waste
370 generation between B05 and D16 are calculated as the amount of indirect waste generation from
371 the consumption of B05 minus that from that of D16.

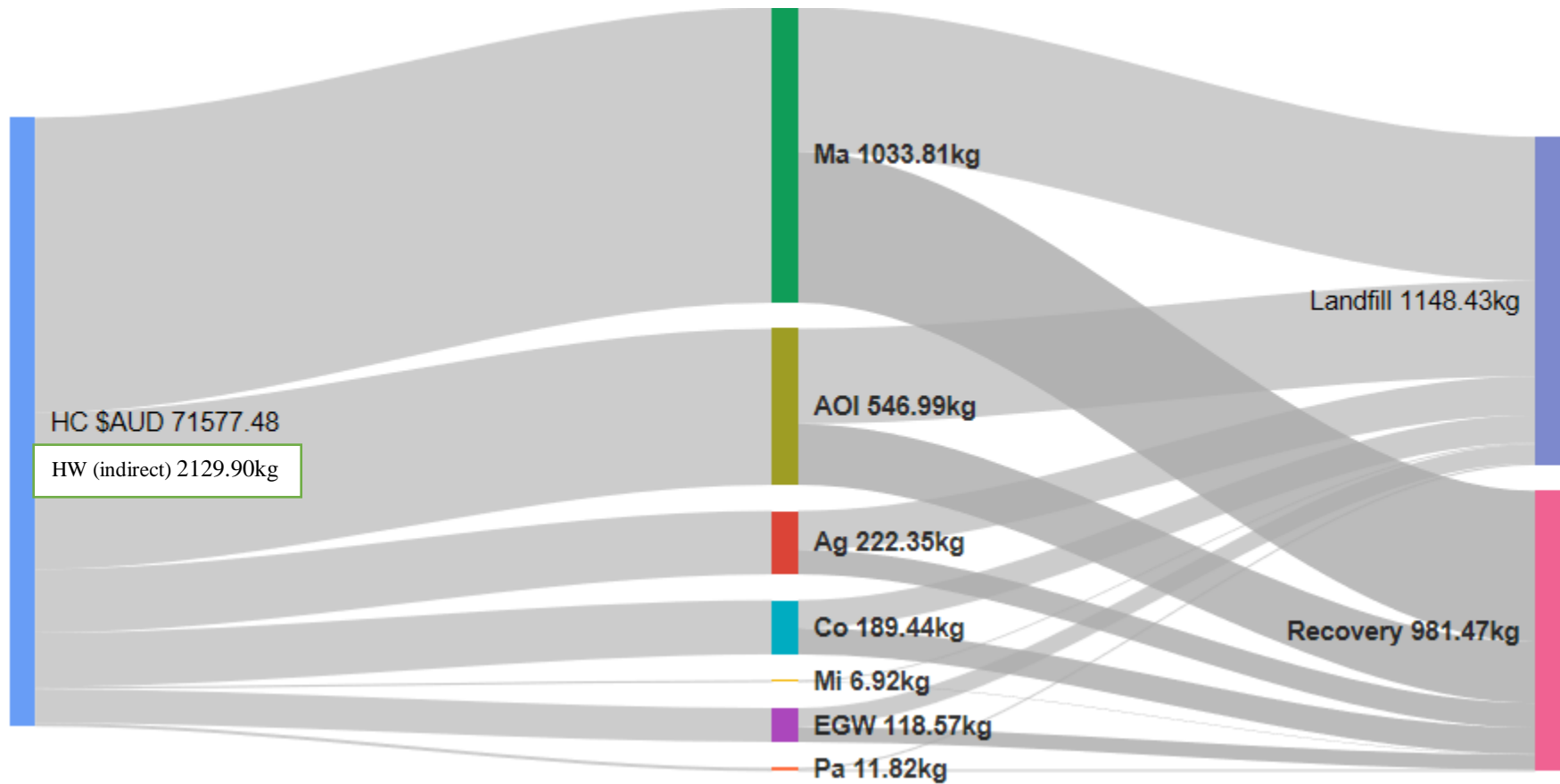
372 Fig. 5 shows the comparative analysis of indirect waste generation for differences between B05 and
373 D16 for scenarios I and II. The total amount of indirect waste generation caused by the consumption
374 of B05 are 99.24 kg more than that of D16 in scenario I. The differences of indirect waste generation
375 in all industrial sectors between B05 and D16 are positive, except for the Agriculture, forestry, and
376 fishing sector and the Electricity, gas, and water sector. The All other industry sector has the largest
377 positive difference for indirect waste generation in scenario I, amounting to 82.6 kg. The total
378 amount of the differences of indirect waste generation (99.24 kg) between B05 and D16 in scenario I

379 are more than that (83.45 kg) in scenario II. The situations for the differences of indirect waste
380 generation in each industrial sector caused by household consumption of B05 and D16 in scenario II
381 are similar to that in scenario I.

382

383 Comparative analysis of indirect waste generation for differences between scenarios I and II for B05
384 and D16 has been presented in Fig. 6. The differences of indirect waste generation between
385 scenarios I and II are calculated as the amount of indirect waste generation in scenario II minus that
386 scenario I for B05 and D16, respectively. The total amount of the indirect waste generation in
387 industrial sectors caused by the household consumption of D16 between scenarios I and II amounts
388 to -169.14 kg. Of this, the largest components were the All other industry (-86.88 kg), the
389 Construction sector (-41.44 kg), and the Electricity, gas, and water sector (-31.26 kg). Difference of
390 indirect waste generation in the Mining sector is the only positive number (8.62 kg). Compared with
391 the data of D16, the household consumption of B05 results in a larger difference of indirect waste
392 generation (-184.91 kg). The differences of indirect waste generation between scenarios I and II for
393 B05 is similar to that for D16.

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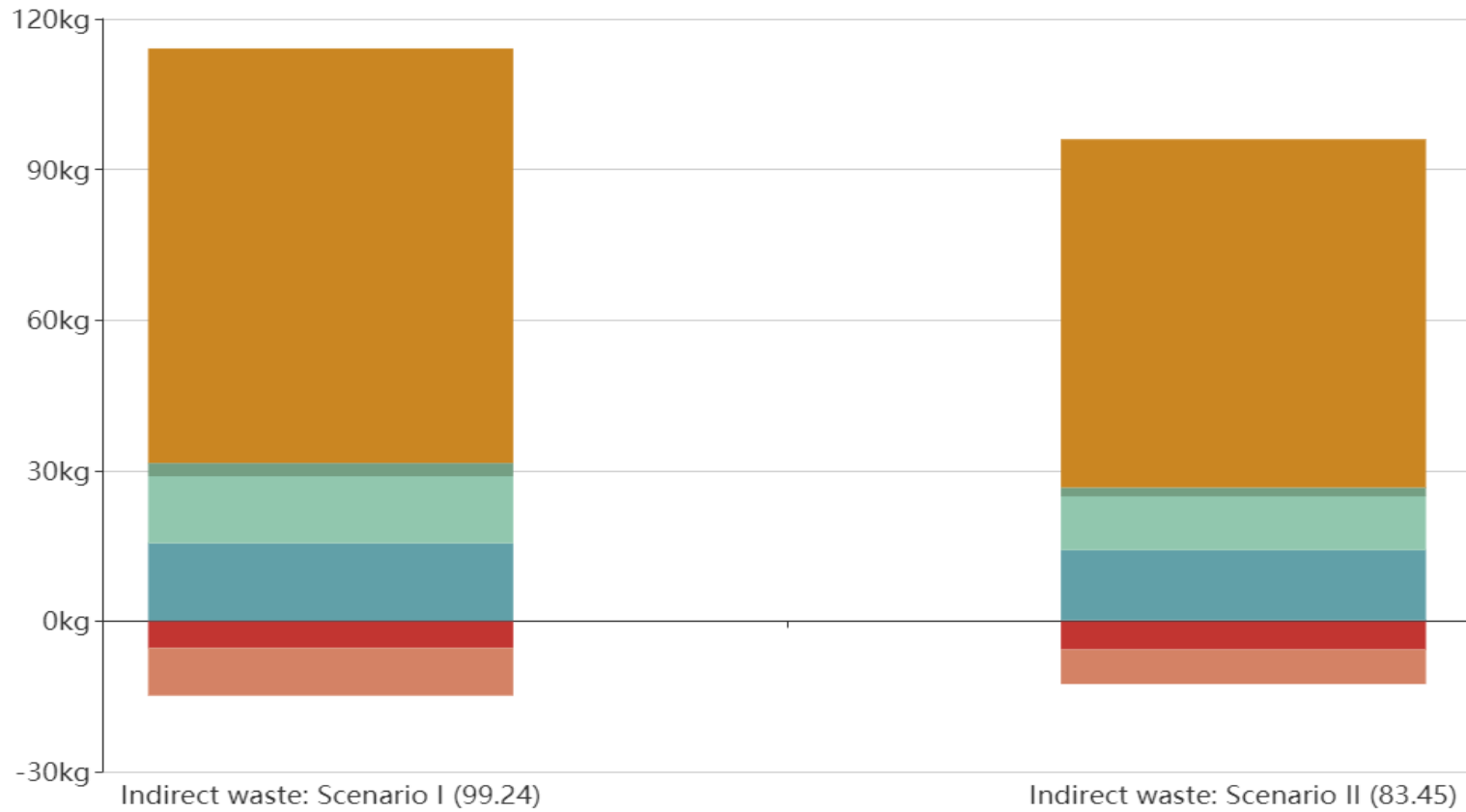
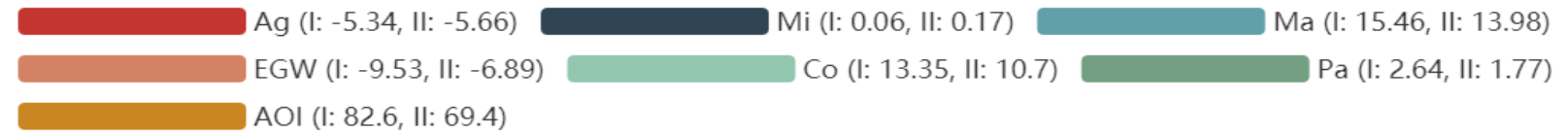
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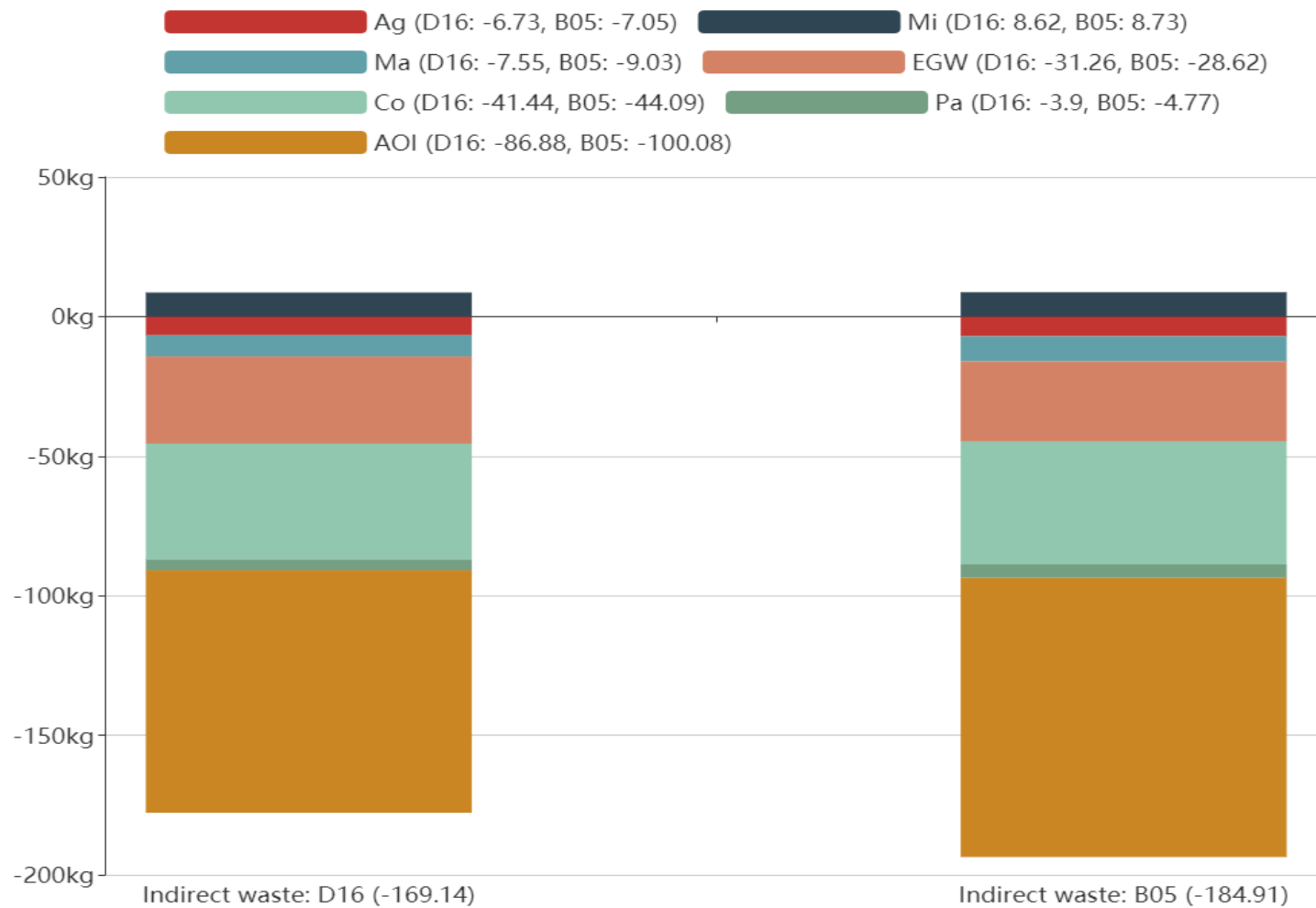
Fig. 1. Waste footprint of industrial sectors in Scenario I; indirect waste generation (industrial sectors) (middle) driven by the household of D16 (left) and treated by the Landfill and Recovery sectors (right). Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water = EGW; Waste management services = WMS; Construction = Co; Public administration = Pa; All other industry = AOI; Household consumption = HC; Household waste = HW.

401



402

403 **Fig. 5.** Comparative analysis of indirect waste generation for differences between B05 and D16 for scenarios I and II (kg). Note: Agriculture, forestry, and fishing
 404 = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water = EGW; Waste management services = WMS; Construction = Co; Public administration = Pa;
 405 All other industry = AOI; Household consumption = HC.



407

408 **Fig. 6.** Comparative analysis of indirect waste generation for differences of scenarios I and II for B05 and D16 (kg). Note: Agriculture, forestry, and fishing = Ag;
409 Mining = Mi; Manufacturing = Ma; Electricity, gas, and water = EGW; Waste management services = WMS; Construction = Co; Public administration = Pa; All
410 other industry = AOI; Household consumption = HC.

411 **3.3 Correlation analysis between output of economy and**
 412 **indirect waste generation in industrial sectors**

413

414 This section aims at exploring the nexus between the output of economy and waste generation in
 415 industrial sectors. The objectives were to perform a) correlation analysis between the output of
 416 economy and indirect waste generation in industrial sectors with the consumption of B05 or D16 in
 417 scenarios I or II, b) correlation analysis between differences of the output of economy and differences of
 418 indirect waste generation in industrial sectors for B05 and D16 in scenarios I or II, and c) correlation
 419 analysis between differences of the output of economy and differences of indirect waste generation in
 420 industrial sectors in scenarios I and II for B05 or D16. The correlation coefficients between the output of
 421 economy and indirect waste generation in industrial sectors are strong and positive (Table 4). Table 5
 422 shows that correlation coefficients between differences of output of economy and differences of
 423 indirect waste generation in industrial sectors for B05 and D16 are 0.9796 in scenario I and 0.9773
 424 scenario II, respectively. It is higher than correlation coefficients between the output of economy and
 425 indirect waste generation in industrial sectors in scenario I for B05 (0.7515) or D16 (0.7470) and in
 426 scenario II for B05 (0.6886) or D16 (0.6887), respectively (Table 4). Table 6 shows that there are weak
 427 nexuses between differences of the output of economy and differences of indirect waste generation in
 428 industrial sectors for B05 and D16 between scenarios I and II.

429 **Table 4** Correlation coefficient for B05 and D16 in scenarios I and II.

Scenarios	Household types	Total output for indirect waste generation
Scenario I	B05	0.7515
	D16	0.7470
Scenario II	B05	0.6886
	D16	0.6887

430

431 **Table 5** Correlation coefficient for differences between B05 and D16 in Scenario I or II.

Scenarios	Household types	Differences of total output for indirect waste generation
-----------	-----------------	---

Scenario I	Between B05 and D16	0.9796
Scenario II	Between B05 and D16	0.9773

432

433

434 **Table 6** Correlation coefficient for differences for B05 and D16 between scenarios I and II.

Household types	Scenarios	Differences of total output for differences of indirect waste generation
B05	Between scenarios I and II	-0.04365
D16	Between scenarios I and II	-0.06789

435

436 3.4 Results of sensitivity analysis

437

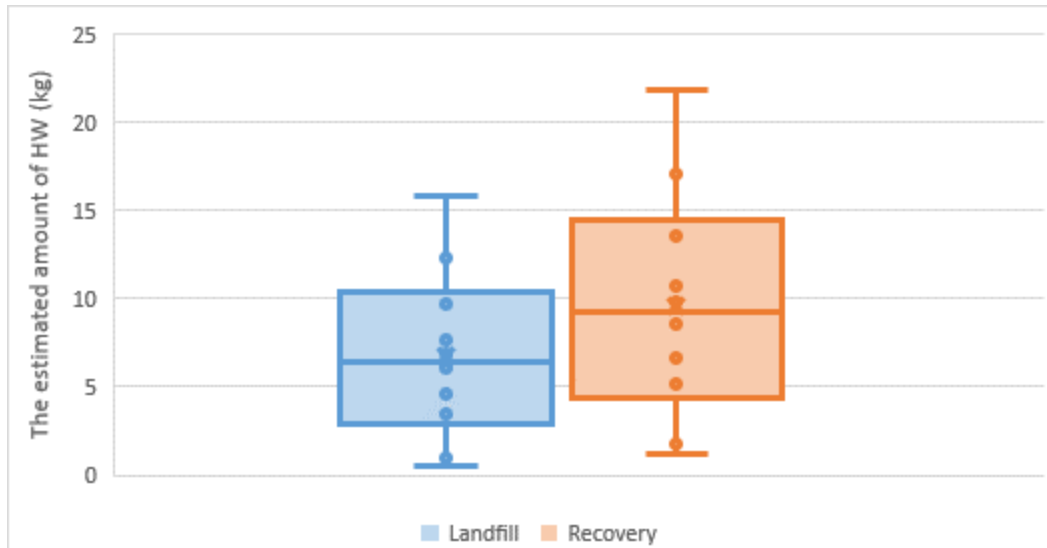
438 In this section, the results based on the calculation of three steps mentioned in Section 2.3 have been
 439 displayed. HW treated by the Landfill sector is considered as an example to illustrate the calculation in
 440 detail. After 5 iterations from the equations 5 to 8, a stable $\mu_n = 6.22$ and $\sigma_n = 3.74$ based on the 7
 441 samples of the Landfill sector was reached. Table 7 shows the 10 values of the amount of HW for the
 442 Landfill sector and the Recovery sector selected from the random sample for $\mu_n = 6.22$ and $\sigma_n = 3.74$
 443 based on normal distributions for D16. Figure 7 displays the Box-and-Whisker Plots of the estimated
 444 amount of HW landfilled and recovered for D16.

445 **Table 7** The estimated amount of HW for the Landfill and Recovery sectors for D16 (kg per week).

Number	1	2	3	4	5	6	7	8	9	10
Landfill (Kilograms)	3.50	9.69	0.91	12.34	6.04	7.60	15.84	6.89	4.58	0.52
Recovery (Kilograms)	5.21	13.53	1.72	17.09	8.62	10.71	21.79	9.76	6.66	1.20

446

447



448

449 **Fig. 7.** Box-and-Whisker Plots of the estimated amount of HW landfilled and recovered for D16.

450 The amount of HW for the Landfill sector for D16 in scenario I were replaced by the values in Table 7.
 451 The other values for the Household sector were kept constant for D16 in scenario I. The 10 WIO tables
 452 for D16 corresponding to the 10 values of the amount of HW for the Landfill sector were then
 453 constructed. This operation was carried out to allow analysis of the uncertainty around the amount of
 454 HW treated by the Landfill sector. Specifically how changes to HW for D16 affects two major indicators:
 455 1) the value of monetary inputs (for the All other industry sector) is linked to demand from households ;
 456 and 2) changes to the value of waste caused by the shifting demand (and waste generation) of the
 457 Household sector.

458 Table 8 reports the coefficients of variation of the amount of HW landfilled and recovered, the most
 459 monetary inputs from the All other industry sector, and the most amount of waste generation by the
 460 Manufacturing sector in 2009–10 and 2010–11. As there was only one value for B05, there was no
 461 formal method to estimate standard deviation with certainty. In order to perform sensitivity analysis,
 462 the research used the standard deviation of the sample of D16 to analyse the sample of B05. Table 9
 463 shows the similar results of B05 in 2009–10 and 2010–11. Coefficient of variation in Tables 8 and 9 is a
 464 measure of relative variability. It is the ratio of the standard deviation of the numbers of estimated
 465 waste generation to the mean of the numbers of estimated waste generation. The coefficients of
 466 variation for 10 variables and 15 variables show the similar result. This indicates that there is no need to
 467 add more variables since adding extra 5 variables did not make any difference for estimated results.

468

469 **Table 8** The coefficients of variation of the amount of HW landfilled and recovered and major indicators for D16.

Year	Waste treatment methods	Indicators	Coefficients of variation
2009–10	Landfilled	The amount of HW	0.7143
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000
	Recovery	The amount of HW	0.6776
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000
2010–11	Landfilled	The amount of HW	0.7143
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000
	Recovery	The amount of HW	0.6776
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000

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480 **Table 9** The coefficients of variation of the amount of HW landfilled and recovered and major indicators for B05.

Year	Waste treatment methods	Indicators	Coefficients of variation
2009–10	Landfilled	The amount of HW	0.7124
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000
	Recovery	The amount of HW	0.7790
		The monetary inputs from the All other industry	0.0001
		The waste generation by the Ma sector	0.0000
2010–11	Landfilled	The amount of HW	0.7124
		The monetary inputs from the All other industry sector	0.0001
		The waste generation by the Ma sector	0.0000
	Recovery	The amount of HW	0.7790
		The monetary inputs from the All other industry I sector	0.0001
		The waste generation by the Ma sector	0.0000

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482

483

4. Discussion

484 This research has proposed a new perspective to assess the nexus between the Australian household
485 consumption and indirect waste generation and treatment. This is explored further using a case study
486 based on the existing Australian WIO model, the Mosaic data for household consumption, and on-site
487 collection data for direct waste generation and treatment. These have different impact perspectives on
488 the research outcomes. Household consumption is the major factor to result in indirect waste
489 generation. The design of different types of scenarios (existed Australian WIO model) provides more
490 details for better understanding the effect of economy on indirect waste generation. The on-site

491 collection for direct household waste data has been integrated in the WIO table and make the table as a
492 whole.

493 The strength of this research lies in its somewhat detailed description of economic activities and waste
494 treatment caused by different patterns of household consumption through the combination of macro-
495 and micro- economic and environmental data related to Australian industrial sectors, different types of
496 household consumption, and waste generation. Most previous research relating to the IO model
497 quantified direct waste generation from average or aggregated household consumption (Wiedmann et
498 al. 2006, Reutter et al. 2017, Reutter et al. 2017) and ignored the fact that household consumption can
499 be categorized into different types depending on different socio-demographic indicators. Although some
500 researchers have analysed the indirect waste generation caused by the household in the supply chain
501 (Parfitt et al. 2010), there is a lack of a detailed analysis about how the patterns of household
502 consumption affect indirect waste generated in the supply chain. Now having shown that this method is
503 feasible, a detailed analysis can be undertake using high resolution input-output models (Lenzen et al
504 2014).

505 The proportion of direct waste generation from the household has been about 25% in the total amount
506 of waste while that of indirect waste generation is about 75%. Similar results have been illustrated by
507 Kim et al. (2017), which have shown that percentage of industrial waste is high with 76.3%, and lower
508 household waste (26.5%). It is worthwhile indicating that this relationship between direct and indirect
509 waste is based only on the scope and availability of data, if the scope of inclusion changes, then this
510 relationship may change. The waste footprints show how the different patterns of household
511 consumption caused indirect waste generated in industrial sectors and treated by waste treatment
512 sectors. As for the same pattern of household consumption, the indirect waste generated in scenario II
513 (the year of input coefficient and Leontief matrix is 2010–11) is less than that in scenario I (the year of
514 input coefficient and Leontief matrix is 2009–10). This change could illustrate the developments that
515 have been found in other studies, for example, cleaner technologies (Ahamed et al. 2016, Yong et al.
516 2016), waste management (Zaman 2015), and economic model (Geissdoerfer et al. 2017, Haupt et al.
517 2017). The Manufacturing sector generated the most amount of indirect waste. This corresponds to the
518 results of other studies generation (Priefer et al. 2016, Van Ewijk and Stegemann 2016) that identified
519 goods, such as food, clothes and electronic (e-) waste, consumed by the household and made by this
520 sector as the main source of indirect waste generation. The waste footprints have illustrated that the
521 total waste generated along the supply chain is about 3 times higher than what households dispose of

522 directly, which is similar to the result from Fry, Lenzen et al. (2016). The B05 has generated more
523 indirect waste than the D16 in the same scenario with more household consumption. The result has
524 been connected with that the higher level of household consumption tends to generate more amounts
525 of waste (Dyson and Chang 2005, Sjöström and Östblom 2010, Suthar and Singh 2015). In the UK the
526 amount of waste generation, such as food, clothing, paper, plastics, electronic (e-) waste, and glass, had
527 an important growth due to the growth in the overall household expenditure: from around £34 billion in
528 1971 to £795 billion in 2006 (Tudor et al. 2011). Although the amount of indirect waste treated by the
529 Landfill sector is more than that by the Recovery sector, the differences between them becomes smaller
530 from scenario I to II. It gives an insight that the Landfill sector will be not a major solution for waste
531 management in Australia (ABC NEWS 2018).

532 The comparative analysis between household consumption of B05 and D16 shows the effects of
533 different patterns of household consumption on indirect waste generation in industrial sectors. The
534 comparative analysis between B05 and D16 for scenarios I and II indicates the largest differences of
535 indirect waste generation occur in the All other industry sector, which contains a series of service
536 sectors including Accommodation and Food services, Rental, Hiring and Real Estate Services,
537 Professional, Scientific and Technical Services, and Arts and Recreation Services (ABS 2008). It indicates
538 that after satisfying the basic human demand for living products, people who spend more money on
539 services, such as education (Smyth et al. 2010, Fagnani and Guimarães 2017), health (Thakur et al. 2015,
540 Almeida et al. 2017), and tourism (Arbulú et al. 2015), can generate more indirect waste. The increase of
541 indirect waste generation in the All other industry sector for scenarios I and II could be explained in part
542 by the growth of food waste in the Food services sector: for example, Reynolds et al. 2015b found an
543 increase in the number of meals eaten outside the home in the context of the increase of the income.
544 For example, the increase of the amount of the UK household waste generation is partly related to a
545 2.1% increase in the number of meals eaten outside the home between 2012 and 2015 (The
546 Environment, Food and Rural Affairs Committee 2017).

547 The negative numbers of indirect waste generation in the comparative analysis based on the same
548 pattern of household consumption between scenarios I and II could indicate that more clean production
549 technologies and environmental strategies have been applied in most industrial sectors to reduce the
550 waste generation. For example, the Construction sector generated less waste in scenario II than scenario
551 I, which can be partly attributed to the technology of Pre-Fabricated Construction (Sandanayake et al.
552 2016) and 'Construction and demolition waste guide – recycling and re-use across the supply chain'

553 (Australian Government Department of Sustainability, Environment, Water, Population and
554 Communities 2011). The only positive number of the differences for the indirect waste generation
555 appears in the Mining sector. It illustrates that as the single largest producer of solid waste in Australia,
556 the Mining sector has resulted in the cumulative solid waste legacy of mining due to the wide
557 application of large-scale open cut mining (Worrall et al. 2009, Mudd 2010).

558 The correlation analysis shows that the differences of household consumption between B05 and D16
559 has strong nexus with the differences of indirect waste generation in scenarios I and II. It further
560 indicates that the household consumption has significant effect on indirect waste generation (Sjöström
561 and Östblom 2010, Suthar and Singh 2015).

562 The results of the sensitivity analysis indicate that the change of the amount of household waste
563 generation in a reasonable range cannot dramatically affect the major economic activities and indirect
564 waste generation. For example, the change in the amount of HW for D16 (The coefficient of variation is
565 0.7143.) has a slight significant change of the monetary inputs from the All other industry sector (The
566 coefficient of variation is 5.5×10^{-5} .), and the amount of waste generation from the Manufacturing sector
567 (The coefficient of variation is 2.7×10^{-5}). It also indirectly reflects that most of waste in the Australian
568 economy caused by the Household consumption is generated in the supply chain, rather than at the
569 household level. Therefore, the data of the amount of waste weighed from on-site audit only performs a
570 benchmark value for the WIO analysis.

571 Finally, our application of WIO analyses the effect of different patterns of household consumption on
572 indirect waste generation by incorporating different types of scenarios. This allows macro- and micro-
573 economic data to be integrated with waste data. This quantitative method would benefit the study of
574 effects of household consumption on waste management in a national scale. It could also be used to
575 assist in the design of environmental policies for different households in terms of environmental impacts
576 related to their different consumption and waste generation patterns.

577 This ability to investigate indirect waste generation from the perspective of different patterns of
578 household consumption is particularly important when considering the rapidly changing demography of
579 Australia, the UK and many other countries globally. The methods proposed in this paper allow the
580 waste management implications of this demographic change to be investigated at a higher level of detail
581 than under previous WIO or other traditional methods.

582

583 5. Conclusions

584

585 The novelty of this research is to analyse the indirect waste generation in the supply chain from the
586 perspective of patterns of household consumption. We combine macro- and micro- economic and
587 environmental data related to Australian industrial sectors, different patterns of household
588 consumption (Mosaic data), and direct waste generation into the WIO model for exploring this nexus in
589 two scenarios. This research has demonstrated it is possible to analyse indirect waste generation and
590 treatment arising from household consumption, this is typically hidden within the Australian economic
591 and waste data. However, the scale of the IO model (8 sector), and the aggregated waste data make this
592 paper more of a proof-of-concept study than a detailed investigation.

593 Results show that indirect waste generation is hidden from the end-user of products and services. We
594 find the level of indirect waste generation for B05 (couples without children who spend most of their
595 time at the office) and D16 (couples without children who are retired and stay at home) is greater than
596 that of direct waste generation for D16 and B05. 75% of Australian household waste generation is
597 related to indirect waste generation. It indicates that the waste generated in the supply chain is much
598 more than the waste generated in the household. Due to this result we encourage the consideration of
599 waste management strategies that conduct waste minimisation across the supply chain, rather than just
600 at the consumer level. The amount of indirect waste generated by B05 is more than that by D16. There
601 are two reasons for this result: 1) B05 spends more time at the office and eat more food outside; and 2)
602 B05 spends more money for their living. Both of them can generate more indirect waste from the supply
603 chain. Policy-makers should levy extra fee for waste generation in terms of household consumption. Our
604 Correlation analysis indicates a clear nexus between household consumption and indirect waste
605 generation. This indicates that technologies and policies published by Australian governments and
606 aimed at reducing waste generation should focus on the supply chain or upstream processes in addition
607 to on-site disposal.

608 However, the patchy economic and waste data regarding household consumption and waste
609 management are a significant hurdle for analysis. First, in relation to the accuracy of the research,
610 although the data of waste generation from on-site collection have limited effects on the research
611 findings, we could further enhance the accuracy with data of waste from more samples of different
612 types of household. Second, if the base data can be matched to the same period(s), the modelling will

613 obtain more accurate and useful results for policy-makers. Finally, this research does not intend to
614 represent an entire class of people nationwide, but calculates for two large groups of the Australian
615 population, how much waste will be indirectly generated in Australian industrial sectors due to their
616 consumption and waste generation.

617 Indeed, a weakness of this paper is that the volumes of waste modelled have been presented and
618 investigated in aggregate with no differentiation or waste composition analysis besides treatment
619 destination. As Mmereki et al. (2016), states "the composition of solid waste varies greatly from country
620 to country and changes significantly with time", this means that: 1) future changes to consumption and
621 production will change the composition of the waste and thus environmental and economic impacts. 2)
622 If this study was conducted in another geography and with other demographic groups the waste
623 compositions will vary due to cultural and geographic factors. This complexity (between aggregated and
624 disaggregated waste, destinations of waste, and cultural and geographic determinates) should be
625 investigated in future research. A method to disaggregate generic waste volumes into component parts
626 using IO tables has been proposed by Reynolds et al (2015a). In future work this method could be
627 extended and linked with the scenarios presented in this paper, or compared with other geographies.

628 Furthermore, the IOT used in this study contains only one aggregated service sector (and only eight
629 aggregated intermediate sectors in total). This aggregation means that differences in service sector
630 consumption between B05 and D16 are not explored fully in our analysis, and the indirect waste
631 generation differences cannot be explored fully. A disaggregated IOT and waste account, along with a
632 full compositional audit of the waste would provide a much richer data source to model. A further
633 weakness of the paper is that the IO tables it uses as a foundation are based on the assumption of
634 domestic technology being identical to global technology (and vice versa). This has some major
635 implications for our findings validation, as indirect waste generation will be embedded in both the global
636 and Australian supply chains, and waste generation and production efficiency differences between
637 supply chains is not currently taken into account.

638 With the above weaknesses in mind, the research presented here integrates the patterns of household
639 consumption into a WIO model (albeit a model with only 8 intermediate sectors, and a single aggregated
640 waste sector) . By using the micro-economic information of household consumption as the major driving
641 force of indirect waste generation, it regards part of the operation of the supply chain as a function to
642 generate waste in order to fulfil the different needs for human well-being. It is important from
643 environmental management perspective to understand indirect waste generation with corresponding

644 implication for the nexus between economy and environmental issues. This research can be used as a
645 bridge between different future household consumption scenarios. Further studies' directions based on
646 this research for waste management are:

- 647 • Collect (disaggregated and detailed) waste data in terms of household types of Mosaic data to
648 form a series of (detailed global or multiregional) WIO models to comprehensively explore the
649 nexus between economic activities and waste generation caused by different types of
650 household types, and

651 apply this method to analyse the indirect energy consumption and greenhouse gas emissions from
652 different types of household consumptions. This research provides a method for obtaining more
653 information regarding nexus between household consumption and indirect waste generation, allowing
654 us to understand the effects of household consumption on indirect waste generated from industrial
655 sectors. It is hoped this new capacity can 1) revitalize discussions around waste management and
656 sustainable development from the perspective of household consumption, and 2) guide future data
657 collection efforts.

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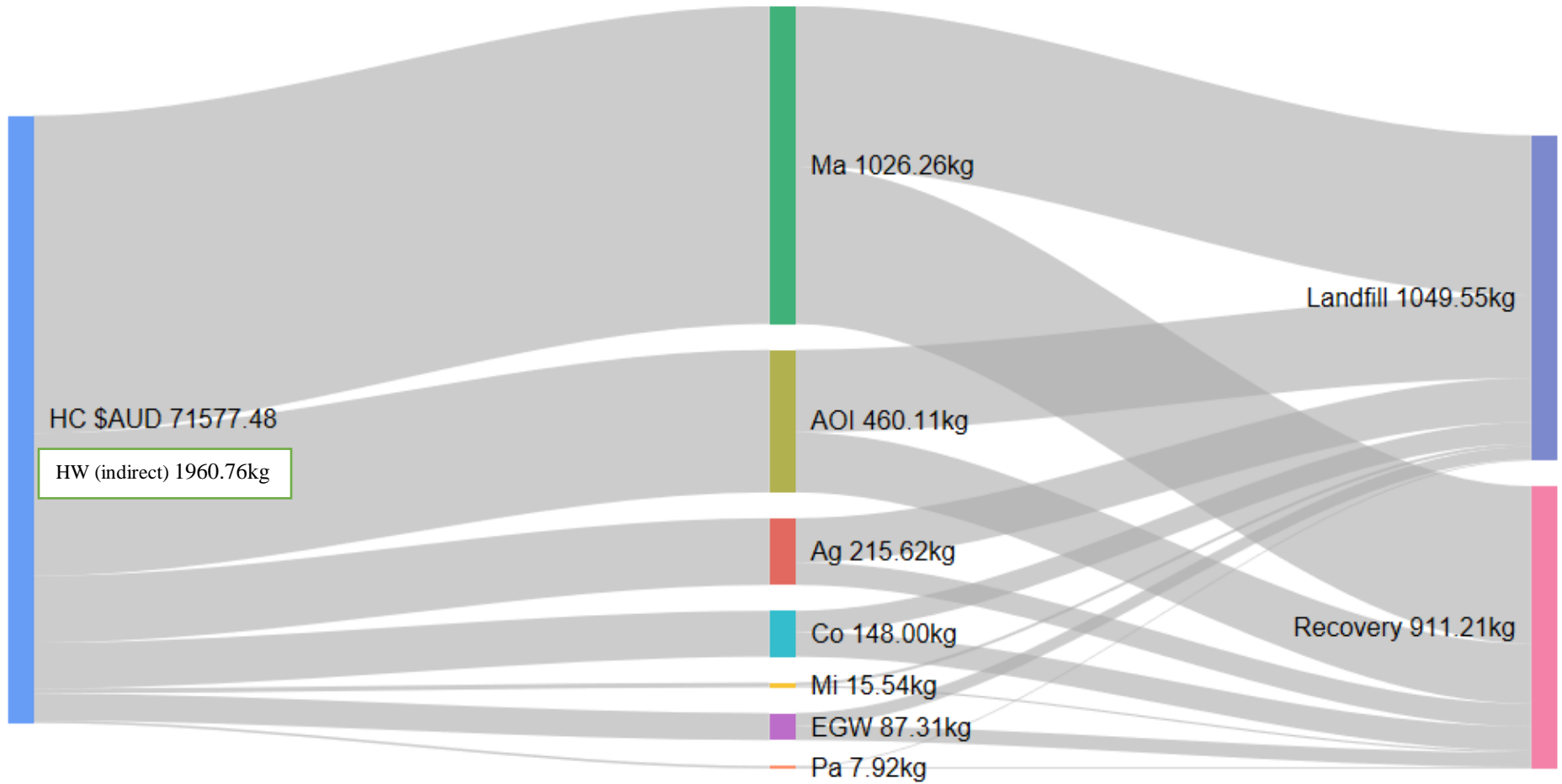
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- 902 Supplementary Appendix
- 903 SA and Adelaide waste composition
- 904

905 Sankey diagrams of additional scenarios

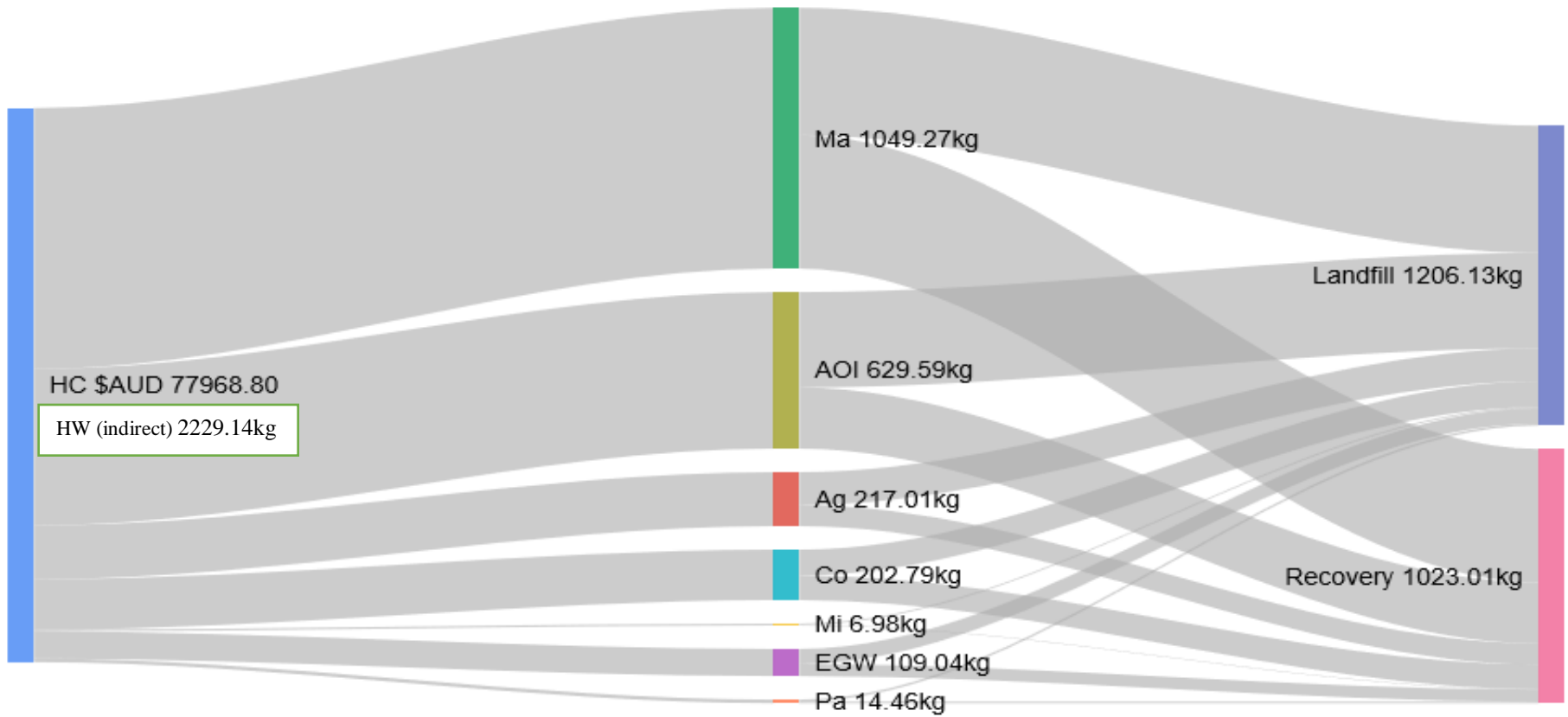
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908 **Fig. 2.** Waste footprint of industrial sectors in Scenario II; indirect waste generation (industrial sectors) (middle) driven by the household of D16 (left) and
909 treated by the Landfill and Recovery sectors (right). Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water =
910 EGW; Waste management services = WMS; Construction = Co; Public administration = Pa; All other industry = AOI; Household consumption = HC.

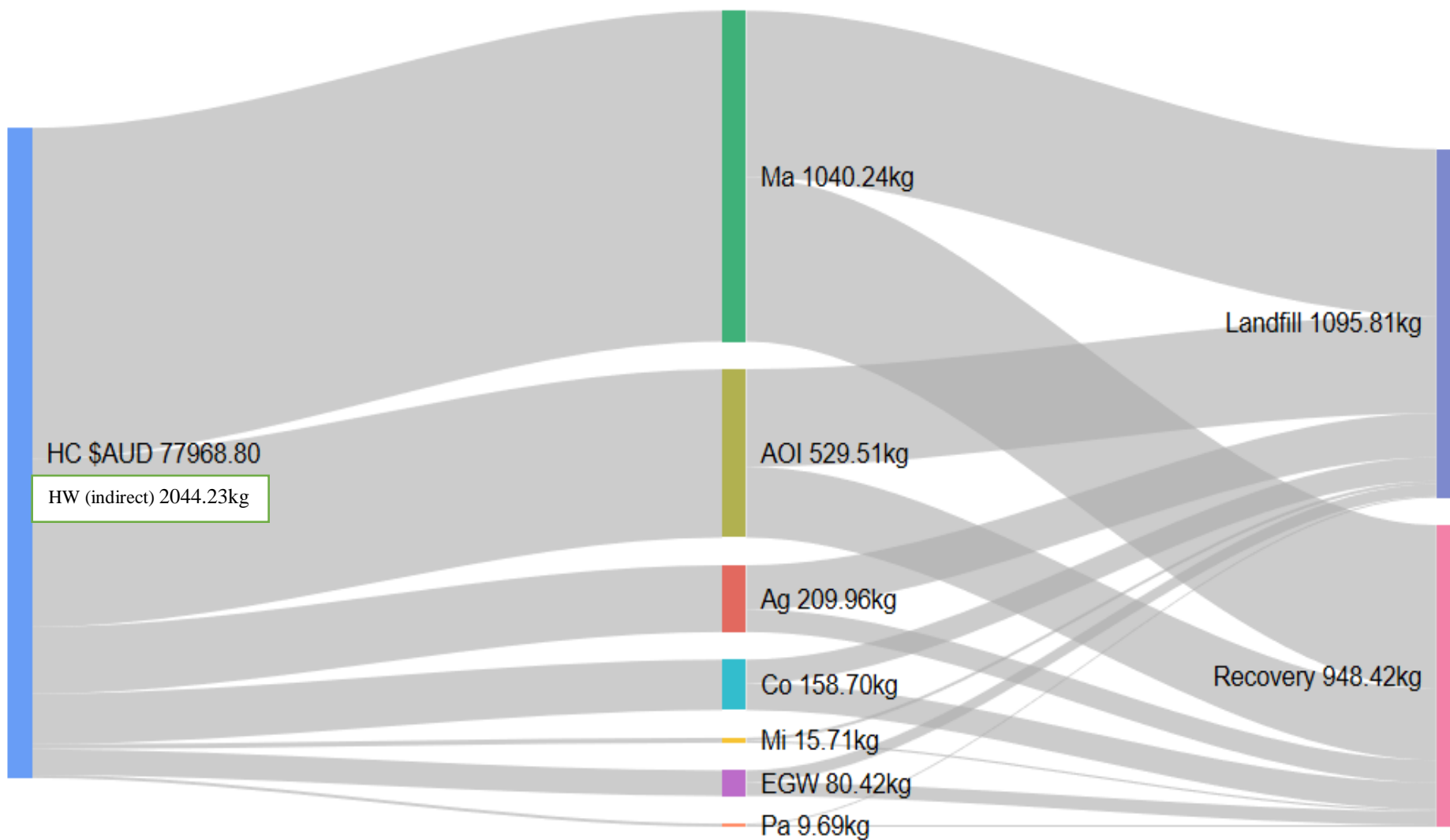
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913 **Fig. 3.** Waste footprint of industrial sectors in Scenario I; indirect waste generation (industrial sectors) (middle) driven by the household of B05 (left) and
914 treated by the Landfill and Recovery sectors (right). Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water =
915 EGW; Waste management services = WMS; Construction = Co; Public administration = Pa; All other industry = AOI; Household consumption = HC.

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 918 **Fig. 4.** Waste footprint of industrial sectors in Scenario II; indirect waste generation (industrial sectors) (middle) driven by the household of B05 (left) and
 919 treated by the Landfill and Recovery sectors (right). Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, and water =
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