



## MUSHNOMICS

Unlocking data-driven innovation for improving productivity and data sharing in mushroom value chain

### Deliverable 1.3 – Gap Analysis

#### Document

<b>Deliverable title</b>	Mushroom Value Chain Analysis
<b>Related Work package</b>	WP1
<b>Responsible Authors</b>	Reed John Cowden and Bhim Bahadur Ghaley
<b>Contributors</b>	Dimitrios Argyropoulos (UCD) Miklós, Gyalai-Korpos (Pilze) Rudolf Erdei (Holisun)
<b>Delivery date</b>	M15 (30/06/2022)

#### Version history

Authors	Comment	Version	Date
Reed Cowden	Draft	1	May 30, 2022
Reed Cowden	Draft	2	July 8, 2022
Reed Cowden	Final	3	

## Disclaimer

This document may contain material that is copyright of certain MUSHNOMICS beneficiaries, and may not be reproduced or copied without permission. All MUSHNOMICS consortium partners have agreed to the full publication of this document. The commercial use of any information contained in this document may require a license from the proprietor of that information.

The MUSHNOMICS Consortium partners are the following:

No	Beneficiary Name	Short Name	Country
1	SC HOLISUN SRL	HS	Romania
2	Department of Plant and Environmental Sciences, University of Copenhagen	UCPH	Denmark
3	Pilze-Nagy Ltd	PILZE	Hungary
4	University College Dublin	UCD	Ireland



*UEFISCDI*



NATIONAL  
RESEARCH, DEVELOPMENT  
AND INNOVATION OFFICE



Ministry of Food, Agriculture  
and Fisheries of Denmark



**gudp**



An Roinn Talmhaíochta,  
Bia agus Mara  
Department of Agriculture,  
Food and the Marine

The information in this document is provided “as-is” and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability.

## Table of contents

1	Executive Summary	7
2	Introduction	8
2.1	Overview of Mushroom Production in EU and Consortium Countries	9
2.2	Waste Production and Associated Emissions in the EU and Consortium Countries	10
3	Methodology	12
4	Mushroom Value Chain Gap Analysis	13
4.1	Mushroom Production Supply and Demand in Denmark	13
4.2	Relevant Waste Sourcing for Mushroom Production in Denmark	14
4.3	Connection Between Waste Generation and Mushroom Production Contexts in Denmark	22
4.4	Mushroom Production Supply and Demand in Ireland	27
4.5	Relevant Waste Sourcing for Mushroom Production in Ireland	28
4.6	Mushroom Production Supply and Demand in Hungary	29
4.7	Relevant Waste Sourcing for Mushroom Production in Hungary	29
4.8	Mushroom Production Supply and Demand in Romania	33
4.9	Relevant Waste Sourcing for Mushroom Production in Romania	33
5	Conclusions	36
6	Acknowledgements	38
7	References	38

## List of Figures

Figure 1. Industry and Household Waste Components over time from 2012-2020 in Denmark. For each year, industry is on the left (in red/orange), with household values on the right (blue/green). 16

Figure 2. Household and Industry biowaste generation and lifecycle as generated from household and industry in Denmark from 2011-2019, shown in tonnes. 19

Figure 3. Copenhagen Price Indices for Danish Waste Management Costs (DKK). Values derived from Copenhagen Municipality prices for waste management into total national waste values. Industry values are red/orange/brown tones, and household are shown blue/green/purple tones. 21

Figure 4. Industry and Household Waste Components over time from 2012-2020 in Hungary. For each year, industry is on the left (in red/orange), with household values on the right (blue/green). 30

Figure 5. Biowaste production and lifecycle as generated from household and industry in Hungary from 2011-2019 in tonnes. 31

Figure 6. Industry and Household Waste Components over time from 2012-2020 in Romania. For each year, industry is on the left (in red/orange), with household values on the right (blue/green). 34

Figure 7. Biowaste production and lifecycle as generated from household and industry in Romania from 2011-2019 in metric tonnes. 34

## List of Tables

- Table 1. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Denmark. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities. 13
- Table 2. Lignocellulosic and Crop Residue Waste Generation in Denmark from 2012 to 2020. 17
- Table 3. Lignocellulosic and Crop Residue Waste Generation for Cereals in Denmark from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019 [62]. All values in tonnes. 17
- Table 4. Supply of waste available for mushroom production and associated greenhouse gas emissions in Denmark. 22
- Table 5. Valorization potential of available waste as mushroom substrate source in Denmark. All values are in 1000 tonnes or 1000 Euros. 24
- Table 6. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Ireland. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities. 27
- Table 7. Lignocellulosic and Crop Residue Waste Generation for Cereals in Ireland from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes. 28
- Table 8. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Hungary. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities. 29
- Table 9. Lignocellulosic and Crop Residue Waste Generation for Cereals in Hungary from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes. 31
- Table 10. Supply of waste available for mushroom production and associated greenhouse gas emissions in Hungary. 32
- Table 11. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Romania. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities. 33
- Table 12. Lignocellulosic and Crop Residue Waste Generation for Cereals in Romania from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes. 35
- Table 13. Supply of waste available for mushroom production and associated greenhouse gases in Romania.* 36

## Acronyms

<b>Acronym</b>	<b>Full Text</b>
EU	European Union
MSW	Municipal Solid Waste
VCA	Value Chain Analysis
DKK	Danish Kroner
HUF	Hungarian Forint
KK	Kobenhavns Kommune
MST	Ministry of Environment of Denmark
SMS	Spent Mushroom Substrate

# **1 Executive Summary**

The dynamics surrounding the mushroom production value chains in the MUSHNOMICS consortium countries (Denmark, Hungary, Ireland, and Romania) have been detailed in *Deliverable 1.1: Mushroom Value Chain Analysis*. Beyond mushroom production, there are important aspects that should also be considered, such as the availability of waste inputs from other activities for use as mushroom production substrate inputs, and the status quo cost and use-pathways associated with their disposal, such as deposition into landfills or incineration. The connection between these two areas—the production of mushrooms and the generation of usable ‘waste’ components in other sectors of the economy, such as agriculture—is the primary focus of *Deliverable 1.3: Gap Analysis*. We have shown here that there are potential synergies that exist between these different sectors of the economy that can provide benefits in both directions; for instance, if crop residues from the agricultural sector are valorized into mushroom substrate instead of being burned in situ or incinerated in a facility, this can localize production and reduce greenhouse gas emissions, with the spent mushroom substrate which is left over after production having a variety of agricultural uses, such as animal feed components or soil amendment. Therefore, this deliverable is focused on tabulating the availability of different sources of ‘waste’ that can be used for different types of mushroom production—primary and secondary decomposers—in the four consortium countries, and collecting data where available about the costs and use-pathways of these waste sources to understand the extant context. We expand on this further by estimating associated greenhouse gas emissions of these ‘waste’ source degradations as well. We then connect the generation of this waste to the potential value generation of utilizing a circular waste valorization intervention via mushroom production. We also investigate the potential downstream applications to discuss whether the ‘waste’ products of mushroom production can also be used in different economic sectors as well. We have shown here in *Deliverable 1.3: Gap Analysis* that there are potential value-creating interventions that can be utilized via existing waste streams in different sectors of the economy to create synergies and utilize circular economic principles in all four consortium countries.

## **2 Introduction**

Mushrooms are the common name for the fruiting bodies of different types of edible fungi. There are two main types of cultivated mushrooms: primary decomposers, also known as white rot fungi, such as Shiitake (*Lentinula edodes*), Oyster (*Pleurotus spp.*), Enoki (*Flammulina velutipes*) or Reishi (*Ganoderma lucidum*), to name a few commonly cultivated varieties [1]–[6]; and secondary decomposing fungi, such as *Agaricus bisporus*, or button mushroom, which requires compost as well as a layer of casing for production [7]–[10]. The casing layer should have a high-water holding capacity, good air pore ratio, and low bulk density [11]. Globally, production of mushrooms has increased 70-fold from 1961 to 2013, from 0.5 million to 34.8 million tonnes, with China producing 30.4 out of 34.8 million tonnes of production in 2013 [12]. The production of mushrooms worldwide was estimated to be worth approximately 42 to 63 billion USD during 2013 [12], [13], with this activity subsequently generating 170-204 million tonnes of spent mushroom substrate (SMS) in 2013 [12], [14]. The production of mushrooms has continued to increase over time, although contemporary accurate data on Chinese production, which is the majority of the world's production, is lacking, which makes accurate tabulation on contemporary global production trends difficult.

As a result of the wide availability and the relatively inexpensive costs for acquiring suitable raw materials for substrate inputs, such as those produced from household or industrial waste, mushroom farming is increasing in popularity and scope, especially in urban and peri-urban environments [15], [16]. For secondary decomposers such as *Agaricus bisporus* (button mushroom), these suitable raw input materials derived from waste include certain types of food waste or animal manure which are composted. Furthermore, for primary decomposers such as *Pleurotus ostreatus* (oyster), or *Lentinula edodes* (shiitake), research has shown that coffee grounds, garden waste, agricultural by-products such as wheat straw, rice husk, corncobs, and cotton waste, as well as paper and cardboard, discarded plant-based textiles, and woody products such as sawdust can all be successfully used as substrate inputs [17]–[24].

With this potential synergy in mind, *Deliverable 1.3: Gap Analysis* (D1.3) is focused on the link between activities in different areas of the economy beyond just mushroom production, distribution, and sales. This macro perspective of D1.3 shows that the potential circularity flows both directions: for instance, the agricultural waste products, such as barley or wheat crop residues, produced in agricultural activities can be used as substrate inputs in mushroom production; furthermore, the spent mushroom substrate (SMS) can then be used as a 'soil amendment'—which has a separate legal classification differentiated from fertilizer, which is regulated in Denmark, for example—in agricultural activities. There are therefore positive,

synergistic feedback loops that can be postulated and exploited between these different economic activities. Therefore, the point of novel value creation in this deliverable connects these two activities that can utilize 'waste' sources as synergistic inputs for other value-creating activities; this perspective utilizes a Gap Analysis of current activities via a lens of 'circularity' within the mushroom production context, while also including a broader economy-wide analysis to determine points, or 'Gaps', of potential intervention.

This deliverable therefore looks at each of the four MUSHNOMICS consortium countries (Denmark, Hungary, Ireland, and Romania) and tabulates the amount of specific types of waste produced in each country that are relevant for mushroom production, while contextualizing this within logistical and economical perspectives that discuss value-creation and likelihood of success, both quantitatively and qualitatively. We also detail the amount of estimated greenhouse gas emissions that are associated with status quo usage and degradation of these waste streams. We therefore have information on the amount of waste, and the associated GHG emissions as indicators of potential gap-exploiting scenarios that can be compared. Where they are available, we also have information on the cost to the user of disposing of waste. Finally, we then take the market price of mushrooms as sold to the consumer, and where available calculate costs to the producers to broadly estimate how much value is generated via mushroom production activities. This then allows us to compare different scenarios for exploiting the existing gaps in mushroom production in these different countries. This deliverable derives much background information from *Deliverable 1.1: Mushroom Value Chain Analysis*, which can be used as a reference for *Deliverable 1.3: Gap Analysis (D1.3)*.

## 2.1 Overview of Mushroom Production in EU and Consortium Countries

In the European Union (EU) 1.06 million tonnes of mushrooms were produced in 2020, with the UK producing 0.1 million tonnes [25]. From 2015 to 2020, the top seven mushroom producers were the same, in descending order: Netherlands, Poland, Spain, United Kingdom, France, Germany, and Ireland. The consortium countries of the MUSHNOMICS project are Denmark, Romania, Ireland, and Hungary, which are significant producers of mushrooms with a combined 9.3% and 12% share of total mushroom production in Europe in 2016 and 2020, respectively. The last year of data for Denmark was in 2016, which showed a production value of 3,930 tonnes; Hungary produced 24,650 tonnes in 2016, and 39,400 tonnes in 2020; Ireland produced 70,020 tonnes in 2016, and 69,260 tonnes in 2020; and Romania produced 14,520 tonnes in 2016 and 14,320 in 2020. In total, these four countries produced 127,662 tonnes in 2020.

Given the standard substrate conversion ratio of 20-25% (average 22.5%), combined with water loss and degradation estimates (45% loss of initial substrate), it can be estimated that the

entire EU produced 2,598,444 tonnes of spent mushroom substrate (SMS) in 2020; the four consortium countries together produced 312,062 tonnes. Managing this waste stream is an important contemporary issue with a wide variety of posited solutions, such as using the SMS as insect feed via vermicomposting, ruminant feed, compost input, soil amendment, agricultural fertilizer pellets, or anaerobically digesting it for the production of biogas [26]. Foregoing this valorization process will require concomitant disposal costs, with different sources putting the cost, based on general waste disposal metrics, at an average of 55.23 Euros/tonne of SMS [27]–[29]. Therefore, the costs of processing this waste stream in Europe can be estimated at 143,512,073 Euros per year; for the four consortium countries, it would cost 17,235,170 Euros per year. Furthermore, these estimates rely purely on the direct monetary costs associated with disposing the waste, without considering the value of valorizing the waste into novel value streams, or even the associated greenhouse gas emissions of waste processing, deposition and transport. This ‘processing’ often takes the form of burning the waste in Denmark to generate electricity, so the associated emissions of this pathway should also be considered as well. Although SMS as a waste stream has many potential uses, it is still not being used to its fullest; in Denmark, many producers deliver their SMS to municipal waste services, where most of it is likely burned. Therefore, emphasizing more circular use of SMS could theoretically reduce costs associated with disposing it, lower GHG emissions, and potentially create value downstream through valorization schemes such as vermicomposting or biogas generation.

## 2.2 Waste Production and Associated Emissions in the EU and Consortium Countries

Concerning a parallel related material stream, during 2018 the EU produced 2,619,880,000 tonnes of waste [30]. In this year, Denmark produced 21,445,206 tonnes of waste, Ireland produced 13,986,757 tonnes, Hungary produced 18,369,585 tonnes, and Romania produced 203,017,193 tonnes of waste [30]. Households in the EU produced a total of 218,390,000 tonnes of waste in 2018, which is only 8.3% of the total waste generated in the EU in 2018, with Industry being responsible for the remaining 91.7%. More specifically, Denmark produced 3,517,972 tonnes of household waste in 2018; Ireland produced 1,591,220 tonnes; Hungary produced 2,742,656 tonnes; and Romania produced 4,178,208 tonnes [31]. In relation to this, the EU emitted 136,038,270 tonnes of CO<sub>2</sub>e in 2018 that were directly linked to waste management practices; Denmark emitted 1,214,950 tonnes; Hungary emitted 3,435,260 tonnes; Ireland emitted 908,850 tonnes; Romania emitted 5,891,790 tonnes CO<sub>2</sub>e in 2018 [31]. Furthermore, in 2018, the EU emitted 4,230,955,884 tonnes of CO<sub>2</sub>e across all industries, households, and activities. Denmark emitted 49,621,299 tonnes; Ireland emitted 62,526,014

tonnes; Hungary emitted 64,735,401 tonnes; and Romania emitted 115,090,959 tonnes of CO<sub>2</sub>e [32].

EU waste generation and associated activity emissions (3.3% of the EU's total emissions) are an essential point of intervention that can be addressed via many possible avenues, especially as waste generation is paired with GDP growth in a 1:1 correlation. Based on previous empirical research which has shown that there has been no decoupling of material footprint (including waste) with GDP growth, it is clear that circular economic principles, including waste valorization, are an essential point of intervention to reduce waste generation in the larger economy, by connecting different industries using reverse logistics and creative synergistic interactions. [33]–[37]. Many existing optimistic assumptions about decoupling resource use with growth rely on ignoring 'indirect' inputs, such as the resource inputs embedded in imported products [38], or they rely on technological solutions that have not been invented yet, and cannot be expected to solve these issues, such as IPCC models relying heavily on BECCS (bioenergy with carbon capture and storage) [36], [38], [39]. The World Bank also echoes these claims, stating that there is a "frequent misconception that technology is the solution to the problem of unmanaged and increasing waste" [40]. With this context in mind, D1.3 undertakes its Gap Analysis using a different focus by investigating the potential of connecting disparate streams associated with economic activities that can produce novel waste valorization options while also creating synergies and benefits such as increasing localized production, thereby reducing logistical problems such as high transport monetary and GHG emissions costs. Positioning novel interventions can also hopefully replace existing polluting activities, such as waste incineration for energy, in situ field burning, or dumping waste in landfills.

Considering the abovementioned related activities of mushroom production and waste generation in Europe, this deliverable is focused on investigating the potential contributions of novel value streams via economic sector circularity to reduce overall waste production and refine mushroom production practices and improve connections and synergies across the supply chain. The primary methodological lens used in this deliverable is a Gap Analysis, which observes and tabulates flows of resources and relationships between components of the mushroom production value chain, while also connecting with other sectors of the economy that can form synergistic relationships. Across these different components of the mushroom production value chain, points of intervention are identified with the purpose of refining existing design flaws, of which waste generation and disposal is a primary concern. The three theoretical pathways to address these design flaws in mushroom production are 'process upgrading', where efficiency of production is the focus; 'product upgrading', where improvements to the product are made; and 'functional upgrading', where the activities of each actor are evaluated. For our Gap Analysis, the primary focus is on "closing the loop" [41]–[43] by focusing not only on

forward logistics, but also reverse logistics, which uses the ‘functional upgrading’ lens to determine how activities between different actors can be improved or utilized to create synergies.

### **3 Methodology**

*Deliverable 1.3: Gap Analysis* continues work conducted for our Value Chain Analysis (VCA) in Deliverable 1.1, which consisted of four key general steps. Firstly, systematically mapping actors across the value chain from production, distribution, markets, to disposal [44]–[49]. Secondly, identifying the distribution of benefits across actors; because of the competitiveness of the mushroom production market, this information is private and difficult to acquire. Thirdly, highlighting the function of governance structures or current events on production activities to help explain their operations and distribution of benefits. Finally, examining the role of upgrading or improving the production process via quality or design features; this is the focus of our continued work here in D1.3. In this regard, we conducted an extensive literature review on mushroom production and statistics in a variety of contexts to collect relevant historical and contemporary data. We used the Royal Danish Library’s online database and Google Scholar for the majority of our literature review [50]. Our key search terms used were, for example, “mushroom + Europe, substrate, value chain analysis; spent mushroom substrate + valorization, downstream, uses, applications, etc.”

Quantitative data for this VCA were derived from a variety of sources. General statistical information was obtained from the FAO, World Bank, IPCC, EUROSTAT, and OECD resources. For Denmark-related statistics, we obtained much of our data from the publicly funded Statbank [51], which is a publicly accessible repository of a wide variety of statistics that are gathered for the entirety of Denmark. Additional Danish information was obtained from the Ministry of Environment publications [52]. For Hungary, statistical information was derived from the Hungarian Statistical Office (KSH) and National Environmental Protection Information System (Országos Környezetvédelmi Információs Rendszer, OKIR).

Beyond our literature review and use of databases, we used field visits, surveys, and interviews to map out the existing network of mushroom activities in consortium countries where possible. We organized our Gap Analysis approach by tracking the activities and material flows along the mushroom value chain, from ‘cradle to grave’, although many studies utilize ‘cradle to gate’, which implies inputs to point of sale. Many perspectives ignore end of life activities, which is one reason we have emphasized that approach here. Based on our materials, we identified and classified the different inputs, activities, outputs, actors, and challenges associated with some selected steps in the mushroom production chain. The process of

undertaking our Gap Analysis also defined the different actors for our stakeholder network, which is seen in *Deliverable 1.2: List of Stakeholders*.

## **4 Mushroom Value Chain Gap Analysis**

### **4.1 Mushroom Production Supply and Demand in Denmark**

Table 1 expands on the Danish VCA conducted in Deliverable 1.1 by showing averaged macro trend data for imports, exports, difference/local demand gap, local production, local consumption, and demand gaps for Denmark. For instance, Denmark imported 10,053 tonnes/year of mushrooms and exported 2,359 tonnes/year on average from 1991-2020; this created a negative trade balance of -7,694 tonnes, which had a cost to purchasers (retailers, grocery stores, and consumers, for example) of approximately -13,972,750 Euros/year on average from 1991-2020. To better contextualize the Gap Analysis conducted here, a production assessment is essential. For instance, from 1991-2017, Denmark produced on average 7,564 tonnes of mushrooms per year, at a cost of around 1,931 Euros/tonne, for a total cost of 14,604,227 Euros/year. Finally, it is worth noting the local demand gap, which tabulates the difference between production and consumption. For instance, Denmark has a negative demand gap of -6,226 tonnes (7,564-13,790 tonnes) of mushrooms per year on average from 1996-2020, which means it consumed 6,226 tonnes more mushrooms per year than it produced. Another way to put this is that Denmark only produced 55% of its national consumption of mushrooms per year on average from 1996-2020. Of the four partner countries, only Denmark had a negative demand gap, which is unexpected considering Denmark is an agriculturally focused export economy. However, as noted previously, Denmark did export around 5,000 tonnes of mushrooms per year around 2004-2007, which fell 80% in 2017 where Denmark exported less than 1,000 tonnes. Table 1 demonstrates that there is a large gap that can be filled by increasing local incorporation of Danish waste into the domestic production of mushrooms in Denmark. It is also worth noting that the high amount of imports in Denmark indicates an unmet consumption differential that can be amended through local production. For instance, Denmark has a relatively high consumption of mushrooms: in 2020, Denmark’s population was 5.81 million, and mushroom consumption was 14,000 tonnes. That’s 2.41 kg/person/year of mushrooms consumed in Denmark.

*Table 1. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Denmark. Values are averages of the listed years in the ‘Data Range’ rows above their corresponding activities.*

COUNTRY	CATEGORIES	IMPORT	EXPORT	LOCAL DEMAND GAP	LOCAL PRODUCTION	LOCAL CONSUMPTION	DEMAND GAP
---------	------------	--------	--------	------------------	------------------	-------------------	------------

	<i>Data Range</i>	<i>(Average for 1996-2020)</i>	<i>(Average for 1996-2020)</i>	<i>(Average for 1996-2020)</i>	<i>(Average for 1991-2017)</i>	<i>(Average for 1996-2020)</i>	<i>(Average for 1996-2020)</i>
<b>DENMARK</b>	<i>Mushroom (tonnes/year)</i>	10,053	2,359	-7,694	7,564	13,790	-6,226
	<i>Monetary value (Euros/year)</i>	18,097,362	4,124,611	-13,972,750	14,604,227	149,469,810	
	<i>Price per tonne (Euros/tonne)</i>	1,800	1,748		1,931	10,839	

Furthermore, beyond mushroom production, it is worth considering the major input to mushroom production: substrate. Denmark currently has no industrial scale domestic production of substrate, imports most of its substrate, and also imports the majority of its substrate input materials from other countries when it does make its own. Some companies do make their own substrate, for instance from wheat straw, imported wood products, or domestic manure. However, many companies import the majority of these input materials, or the substrate entirely, from places like Sweden, Poland, Germany, the Baltic states, or the Netherlands, to name a few examples. Based on the amount of mushrooms produced on average per year domestically (7,564 tonnes/year) we can estimate the amount of substrate used, given the common conversion ratio of around 20-25% (average 22.5%) of gross substrate. Therefore, the amount of substrate that was consumed in Denmark was around 33,618 tonnes per year on average from 1996-2020, with an estimated cost of 55,832,388 Euros. Denmark could therefore benefit by producing their own substrate domestically by connecting with available substrate input sources generated in other sectors of economic activity. This is another gap that can be addressed via our analysis here.

## 4.2 Relevant Waste Sourcing for Mushroom Production in Denmark

The world bank notes that 1.6 billion tonnes of carbon dioxide equivalent (CO<sub>2</sub>e) were generated globally from solid waste treatment and disposal in 2016, which was 3.2% of the total global emissions (49.4 Gt CO<sub>2</sub>e). Furthermore, the world bank estimated that in 2016, approximately 2 billion tonnes of municipal solid waste were generated, which is only expected to increase over time [29]. The amount of generated municipal solid waste is expected to increase to 2.38 billion tonnes by 2050. It is worth noting that only around 20% of these waste streams are recycled or valorized [53]. In Denmark, all waste disposal methods, including recycling, have stayed relatively stable since 2015, with around 46% of waste being collected for recycling, 25% collected for final recovery, 25% being incinerated, and 4% deposited in landfills [54]–[56]. Therefore, there is an evident need to capitalize on these existing waste streams, as the production of waste is a design flaw with the majority of these discarded materials having

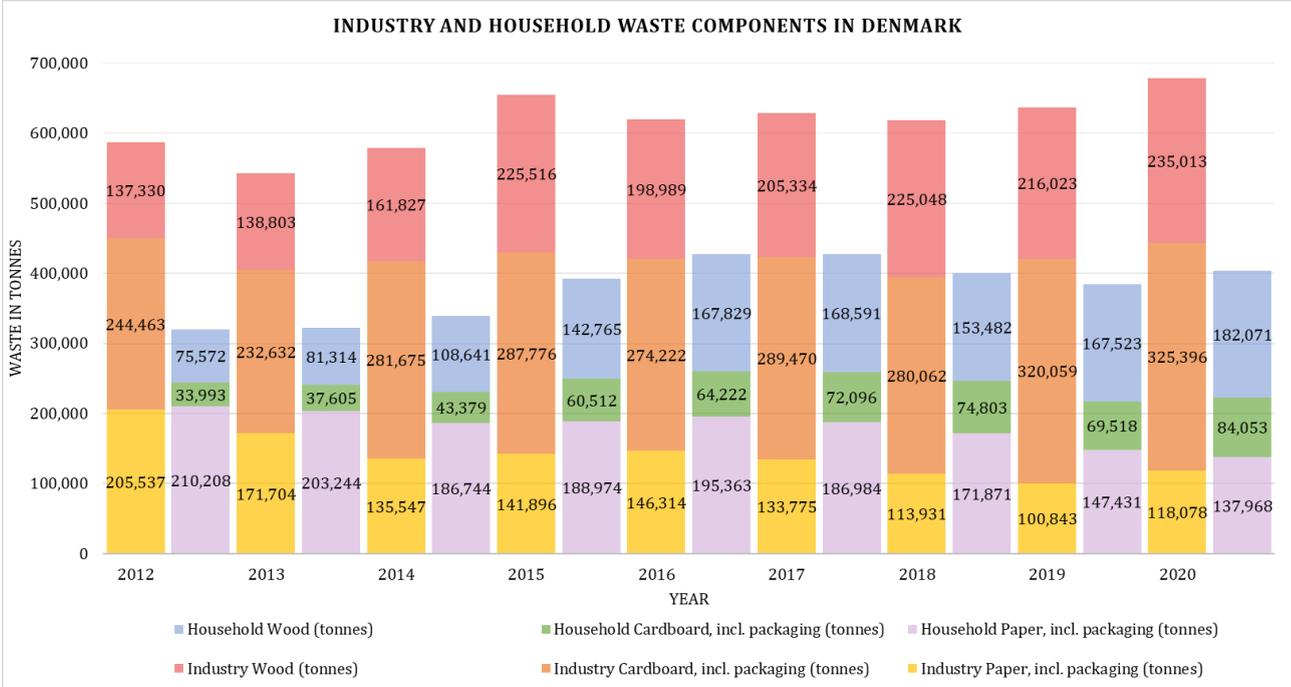
various potential downstream uses. This design flaw demands addressing, not only through theoretical 'design improvement' solutions, but through connections and synergies between different existing parts of the economy that already operate at scale. For instance, the World Bank notes that in 2016, food and garden waste accounted for 44% of total solid waste, paper and cardboard accounted for 17%, and wood accounted for 2% [29]. These three categories are all usable substrate input sources for mushroom production, although they do require processing into usable form. Therefore, valorization of a mere 10% of these three waste streams (which combined constitute 63% of the total solid waste), could reduce emissions by 101 million tonnes of CO<sub>2</sub>e globally, which is nearly the entire emissions of Denmark in 2018. There are of course material inputs and emissions associated with transporting, treating, and building up mushroom production infrastructure, but the potential for emissions reductions is possible via valorization schemes.

In 2020, Denmark produced 21,801,478 tonnes of total waste, including soil [57]. In 2018, where Denmark produced 17,885,912 tonnes of waste (including soil), the greenhouse gas (GHG) emissions of waste disposal were 4,397,000 tonnes CO<sub>2</sub>e [57]. This means that, for every tonne of waste produced, around 0.25 tonnes of CO<sub>2</sub>e emissions are associated with disposal. The total direct GHG emissions in Denmark in 2018 were 106,212,000 tonnes CO<sub>2</sub>e, for all industries, households, and activities [57]. With a population of 5,794,000 in 2018 in Denmark, this means per capita emissions of the entire economy were 18.33 tonnes per person. This is higher than other statistics, given that it includes industry actions that may be associated with export-oriented activities, such as pig farming, which is ultimately accounted for in other countries. More traditional accounting methods from the World Bank state that per capita emissions in 2018 were 5.761 tonnes per person, which is consumption-focused [58]. This effectively means that 12.57 tonnes of CO<sub>2</sub>e per person are embedded in exported materials or processes that are not included in the domestic consumption-based per capita emissions value. The Danish Environmental Agency [54]–[56] has also published data on the waste generation dynamics in Denmark. For instance, they note that the amount of generated municipal waste increased from 799 kg/person to 842 kg/person from 2018 to 2019. Comparatively, Denmark had the highest municipal waste intensity value of all other OECD nations, at around 790 kg of waste per capita in 2017, with a greater value than the United States [59].

As Figure 1 shows, the total industry generation of lignocellulosic waste (LCW)—paper, cardboard, and woody material—in Denmark was 710,483 tonnes, while for households it was 478,124 tonnes in 2020. The total waste generation for these two categories in 2020 was therefore 1,188,607 tonnes. Figure 1 shows the specific LCW fractions that can potentially be utilized via waste valorization interventions, such as cardboard waste whose production rose from 244,463 tonnes in 2015 to 325,396 tonnes in 2019 for industry, and from 33,993 to 84,053

tonnes for households over the same period. Figure 1 also shows that for industry, the largest (by weight) waste generation category was paper and cardboard; for household, it was woody material. In general, over this time period, households generated only 58% of the amount of industry waste.

Figure 1. Industry and Household Waste Components over time from 2012-2020 in Denmark. For each year, industry is on the left (in red/orange), with household values on the right (blue/green).



In Denmark, because of the tabulation practices, there is another large LCW category that is not included under ‘industry’ in these estimates: crop residues. In 2019, Denmark produced 20,974,513 tonnes of crop residues (Table 2), which is almost as much as the entire ‘total waste, including soil’ category for all of Denmark in 2019. This is a result of Denmark’s large agriculture export-oriented economy, where 61% of the land in 2018 was cultivated for arable production, which is very high compared to the EU average of 24.7% [60]. For some context, in 2019, Ireland produced 28,919,568 tonnes of crop residue; Hungary produced 18,505,826 tonnes; and Romania produced 28,472,086 tonnes [61]. The industry and household LCW, including the crop residues, are a huge potential input material for mushroom substrate, especially for primary decomposers such as *Pleurotus spp.*, which can grow on LCW with limited preparation required, depending on the quality and status of the material, and the genetics of the fungi. This is discussed in greater detail in Section 4.3. Table 2 also shows the waste intensity metric, which details the cost (in million Danish Kroners (DKK)) associated with each tonne of waste produced; in 2020, for instance, generating 0.52 tonnes of waste would cost 1 million DKK. Overall, the general trend shows a 15% improvement in waste intensity over time, which is likely the result of improved efficiency of collection, disposal, or recycling methods.

Table 2. Lignocellulosic and Crop Residue Waste Generation in Denmark from 2012 to 2020.

Year	Waste Intensity (tonnes per mil DKK)	Industry and Household Total (tonnes)	Crop Residue total (tonnes)
2012	0.61	942,434	20,768,446
2013	0.57	897,269	19,136,184
2014	0.58	953,271	19,964,308
2015	0.64	1,090,416	18,374,888
2016	0.57	1,092,806	19,865,461
2017	0.57	1,119,745	19,366,755
2018	0.52	1,095,000	16,790,616
2019	0.50	1,106,917	20,974,513
2020	0.52	1,188,607	No Data

Table 3 expands on the general ‘crop residue’ information in Table 2 by showing in detail the different types of crop residues that are estimated to have been generated in Denmark from 2010 to 2016. This information is derived from a paper by Bedoic, Cosic, and Duic (2019) [62], who used different models to calculate the amount of crop residues that were generated in each year for all the countries in the EU. They also have data on Fruit, Vegetable, and Animal products as well; for the purposes of this deliverable, we have only used the Cereal category, as this is of the highest relevance for use as inputs for mushroom production substrate. The highest production values for Denmark are Barley Straw (with an average of 4.41 million tonnes generated per year) and Wheat straw (with an average of 6.82 million tonnes generated per year), both of which are usable substrate inputs.

Table 3. Lignocellulosic and Crop Residue Waste Generation for Cereals in Denmark from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019 [62]). All values in tonnes.

WASTE SOURCE TYPE	2010	2011	2012	2013	2014	2015	2016	MIN	MAX	AVG
BARLEY STRAW	3,594,889	3,918,652	4,894,042	4,762,843	4,277,747	4,649,615	4,762,477	3,594,889	4,894,042	4,408,609
BARLEY BRAN	740,478	783,166	976,967	1,034,373	866,626	936,887	1,038,921	740,478	1,038,921	911,060
BARLEY HULL	624,778	660,796	824,316	872,753	731,215	790,498	876,590	624,778	876,590	768,707

CORN STALK	107,956	130,637	177,410	178,820	172,200	125,188	103,463	103,463	178,820	142,239
CORN HUSK	11,293	13,665	18,558	18,705	18,013	13,095	10,823	10,823	18,705	14,879
CORN COB	23,037	27,877	37,857	38,158	36,746	26,714	22,078	22,078	38,158	30,352
CORN BRAN	12,140	10,683	23,872	38,830	17,491	15,707	17,956	10,683	38,830	19,526
TRITICALE STRAW	438,350	341,000	283,175	183,825	236,950	202,625	138,875	138,875	438,350	260,686
TRITICALE BRAN	28,111	21,839	20,126	14,994	16,402	17,064	11,597	11,597	28,111	18,591
OAT STRAW	270,841	276,536	359,053	369,116	244,885	273,896	367,924	244,885	369,116	308,893
OAT BRAN	31,891	31,409	40,939	41,751	29,708	34,873	42,721	29,708	42,721	36,184
OAT HULL	61,656	60,723	79,149	80,719	57,435	67,420	82,594	57,435	82,594	69,957
RICE STRAW	0	0	0	0	0	0	0	0	0	0
RICE BRAN	429	821	296	36	660	0	371	0	821	373
RICE HUSK	1,115	2,133	770	94	1,716	0	963	0	2,133	970
ROTTEN RICE	7,771	7,807	7,835	7,866	7,901	7,946	8,013	7,771	8,013	7,877
RYE STRAW	358,281	0	0	0	0	1,106,379	827,211	0	1,106,379	327,410
RYE BRAN	27,785	0	0	10,867	7,325	98,531	74,335	0	98,531	31,263
WHEAT STRAW	7,201,526	6,876,317	6,440,371	5,899,680	7,334,467	7,158,974	5,979,816	5,899,680	7,334,467	6,818,556
WHEAT BRAN	654,180	721,283	712,319	612,300	753,709	687,305	583,029	583,029	753,709	674,875

Furthermore, another waste category apart from industry and household LCW and crop residues with applications for mushroom production concerns biowaste: food waste, garden waste, and miscellaneous biodegradable waste, which does not include sewage. This biowaste can be a useful input for secondary decomposers, such as *Agaricus bisporus*, once it has been composted, which is itself a sanitation process if heated high enough (generally past 60 degrees Celsius at a minimum). Figure 2 shows that, in 2019, Danish households produced 928,805 tonnes of biowaste, with approximately 51,497 tonnes of said waste (5.5% of total biowaste) being used for energy generation via incineration. This percentage is likely higher than listed, as much of the 877,036 tonnes of biowaste which is collected curbside by waste management companies with the purpose of recovery ends up incinerated. It has been noted by an interviewee that this ‘recovered materials’ value does not reflect materials actually recovered for recycling, but in fact just tabulates the gross amount that is *intended* for recovery. The actual recovery value is much lower, and an exact value is not available. For instance, only 14,139 tonnes of ‘recovered materials’ are listed as being intended for incineration in 2019, which is a very low percentage of the total (1.6%). However, a publication by the Ministry of Environment

(MST.dk) stated that from 2018-2019, the rate of collecting materials for recycling increased from 45 to 47% of total collected waste, with the rate of incineration staying the same at 25%. Therefore, we can assume that a similar proportion (25%) of biowaste was therefore likely incinerated. This rate can also be estimated for LCW; the amount is likely even higher than 25% for crop residues, as 7% of Denmark's total renewable energy comes from burning straw [63]. Overall, household generation of biowaste has been steadily increasing from 2011 to 2019, with an increase of 55%. The only year with a drop was 2018, which interestingly corresponded with a massive increase in industry generation of biowaste, up from around 400,000 tonnes up to 810,000 tonnes, more than doubling their share.

Figure 2. Household and Industry biowaste generation and lifecycle as generated from household and industry in Denmark from 2011-2019, shown in tonnes.

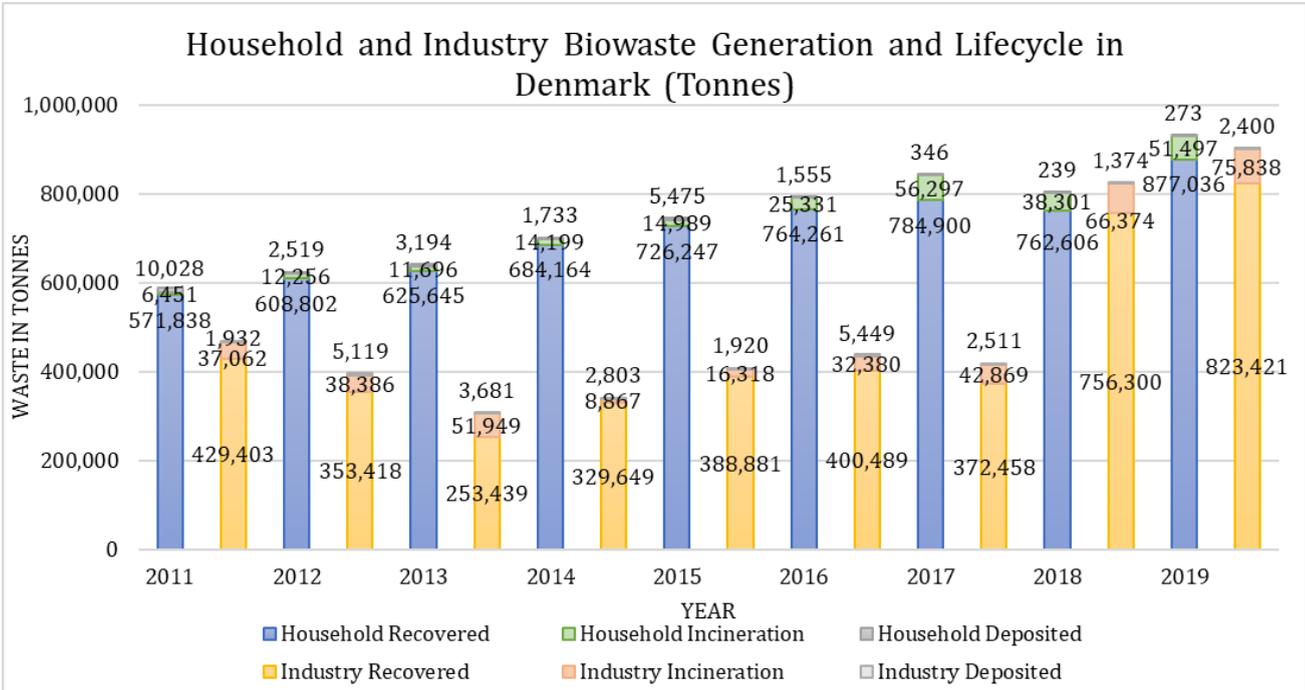


Figure 2 also shows that industry in Denmark generated 901,660 tonnes of biodegradable waste in 2019 with 823,421 tonnes of this being listed as recovered. As previously mentioned, much of this latter value is likely incinerated. In 2019, only 75,838 tonnes (9.2% of recovered materials) of industry biowaste were listed as expressly collected for the purposes of incineration. Furthermore, about 2,400 tonnes of biodegradable waste was deposited in landfills in 2019. More specifically, the category of ‘agriculture and horticulture’, a subset of the total ‘Industry’ category, has important contextual information as well, with around 275,103 tonnes of biodegradable waste (31% of total industry biowaste production) generated in 2019. The recovered materials were listed as 251,121 tonnes, with around 23,894 tonnes intended for incineration in 2019. For agriculture, and industry at large, we can also assume a similar real rate of incineration around 25%, according to the MST. This large pool of biowaste material has

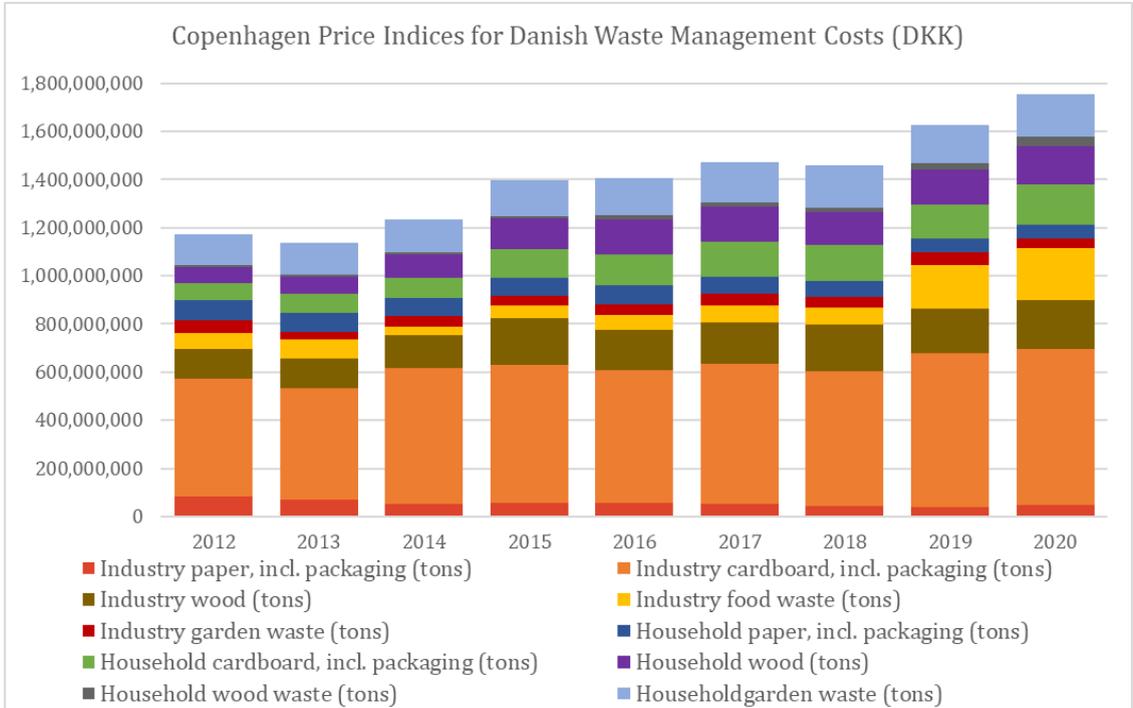
high potential for valorization, as it is unlikely to be highly processed, unlike components of the LCW waste generation category, such as cardboard and paper. This primes the utilization of the biowaste from agriculture and horticulture as a high priority for potential valorization schemes. Overall, industry generation of biowaste has been going through different stages of decreasing from 2011 to 2013, and increasing generally from 2014 to 2018, past which a massive doubling of waste generation occurred. This is likely due to differences in tabulation methodology utilized by Statbank.

Interestingly, Danish households deposited (in landfills) 10,028 tonnes of biowaste in 2011, with only 273 tonnes being deposited in 2019; for industry, only 87 tonnes were deposited in landfills in 2019. Current practices therefore show an intent towards circularity, but much of the existing waste streams are instead incinerated for energy production, which is nonetheless arguably an improvement over open decay via deposition in landfills, which saw much more activity in 2011. However, the reliance on incineration is not an ideal practice, especially considering the availability of utilizing existing wind sources for energy production in Denmark, and considering the embedded value of biomass intended for incineration, which can be transformed into downstream products such as mushrooms. Correspondence with Kobenhavn Kommune (Copenhagen Municipality) noted that all waste streams have lower CO<sub>2</sub>e emissions via recycling instead of incinerating, which supports the suggested valorization scheme of utilizing these waste streams as recycled substrate inputs. This indicates an existing need to improve the rates of recycling and waste valorization of these value streams, instead of relying on incineration. This would improve both the CO<sub>2</sub>e emissions of these activities, but would also create novel value streams as well, such as utilizing the waste as an input for mushroom production. Ultimately, reducing the amount of waste incinerated would also hopefully result in downstream increases in renewable sources of energy production, such as increasing wind and solar utilization.

Beyond accounting for waste generation amounts, it is also useful to consider the practicalities of cost that current waste management schemes incur. For instance, an interview with Kobenhavn Kommune (KK) offered insight into these costs: they state that the cost of composting garden waste is approximately 225 DKK/tonne; larger branches are separated and sent for incineration, which costs 900 DKK/tonne. They note that cardboard is sold for 500 DKK/tonne, but it costs 2,500 DKK to collect, with a net cost of 2,000 DKK/tonne. Paper is sold for 600 DKK/tonne, but costs 1,000 DKK/tonne to collect, with a net cost of 400 DKK/tonne. Food waste costs approximately 300 DKK/tonne, which includes transportation and labor costs of loading/unloading material. Using these values, we created Figure 3, which shows the costs of waste management for both industry and households in Denmark over time for both LCW and biowaste categories using these price metrics. This is a good way to compare price outcomes

when determining whether mushroom substrate interventions are justified; for instance, in 2020, there was an estimated cost of 1,755,810,125 DKK (235,995,008 Euros) for all LCW and biowaste disposal activities. Considering that this value is a net cost, which includes the sale price of at least some components of the waste, it is a good threshold for comparing the cost of making mushroom substrate; the net cost should also be considered for mushrooms, as there is a large amount of value created via mushroom cultivation and sales. For instance, a threshold metric could be made based on the value that mushrooms generate per tonne of waste, and compare these to the current prices listed above. If mushrooms generate more value, then they are a justifiable intervention. Section 4.3 goes into more detail on this value generation comparison.

Figure 3. Copenhagen Price Indices for Danish Waste Management Costs (DKK). Values derived from Copenhagen Municipality prices for waste management into total national waste values. Industry values are red/orange/brown tones, and household are shown blue/green/purple tones.



and household are shown blue/green/purple tones.

Table 4 further expands on the costs of current waste management pathways by showing the different supplies of waste available in Denmark for the production of mushrooms, with the further context of CO2e emissions embedded within the materials, and those associated with incineration estimations. The total average values from 2012-2020 for industry and household categories have been shown for each specific LCW, crop residue, and biowaste category (e.g. Figures 1 and 2, and Tables 2 and 3). We have taken this analysis one step further by looking at the research that analyzes the life cycle and embedded CO2e of these materials; this was done using a 'cradle to grave' assessment, where the cradle to gate values were combined with CO2e

emissions associated with incineration. To indicate some of the physical embedded value of these waste streams, we have also taken values from the literature on the lignocellulosic content as well, as this is the primary mushroom feed source. Overall, the waste with potential use for mushroom production in Denmark has the potential to emit 33,032,335 tonnes of CO<sub>2</sub>e via cradle to grave estimations; if we assume a consistent value of 25% of waste in Denmark being incinerated, we can estimate that 8,258,084 tonnes of CO<sub>2</sub>e emissions will be released via burning these specific materials; replacing this with wind energy, and instead using the waste as mushroom substrate can replace these emissions or reduce their rate of release, as incineration has immediate emissions consequences. It is likely that the potential emissions are much higher than 8.3 million tonnes CO<sub>2</sub>e, as Denmark obtains 7% of its renewable energy from burning straw which amounts to 17.22 Petajoules [64].

Crop residues, including straw, are not calculated as ‘waste,’ which means that the 25% incineration value does not account for crop residues being burned. In line with this, crop residues alone have the potential to emit 26,454,968 tonnes CO<sub>2</sub>e (80% of the total), due to the incredibly large amount of residues generated via agricultural activities. Therefore, by classifying burnable crop residues as ‘non-waste’ Denmark can claim to recycle a much larger proportion of their waste than they do in reality. Because crop residues are so widely available in Denmark, and because they are a reliable and common input for mushroom production, a deeper focus on mitigation activities is warranted that can incorporate them into mushroom production activities. For instance, we can estimate some reductions in CO<sub>2</sub>e emissions by valorizing agricultural waste: crop burning alone was responsible for 3.5% of total global CO<sub>2</sub>e emissions in 2016 [29]. This translates to 1.73 billion tonnes of CO<sub>2</sub>e that are emitted from burning crop residues. In Denmark, over 10 million tonnes of CO<sub>2</sub>e were emitted in 2016 directly from agriculture alone. The next largest portion of the total CO<sub>2</sub>e emissions is biodegradable waste, which has the potential to emit 4,649,381 tonnes of CO<sub>2</sub>e. Wood, cardboard, and paper are the next greatest potential emitters, in descending order. Overall, Table 4 details the connection between waste generation and CO<sub>2</sub> emissions to help contextualize the argument for justifying utilization of these wastes in mushroom production valorization schemes instead of incinerating or depositing them in landfills.

*Table 4. Supply of waste available for mushroom production and associated greenhouse gas emissions in Denmark.*

Waste Source (average from 2012-2020)	Paper	Cardboard	Wood	Crop residues	Biodegradable waste	Total	Proportional Incineration (25%)
Industry (tonnes waste)	140,847	281,751	193,765	20,349,975	901,660	21,867,997	
Household (tonnes waste)	321,824	341,771	332,408	0	928,805	1,924,807	

GHG emissions (tonnes CO2e/tonne waste)	0.94 [65]	0.96 [66]	1.65-1.8 [67]	1.30 [68]	2.54 [69]		
Potential GHG emissions	434,911	598,581	894,494	26,454,968	4,649,381	33,032,335	8,258,084
Lignocellulosic content (%)	87.25 % [70]	83.8 % [70]	95.00% [71]	97.5% [72]	35.83%		

### 4.3 Connection Between Waste Generation and Mushroom Production Contexts in Denmark

The previous two sections (4.1 and 4.2) detailed two separate but related material flow dynamics in Denmark, both of which directly inform our Gap Analysis. The first section reviewed the production of mushrooms in Denmark (with a more in-depth focus available in *Deliverable 1.1: Mushroom Value Chain Analysis*), while the second section discussed the statistics on waste generation, including cost and GHG emission estimations. Based on the life history traits of mushrooms, such as *Pleurotus* spp. or *Agaricus bisporus*, our Gap Analysis shows that there are large interventions and valorization pathways that exist in the waste generation sector of our economy. These two sections are crucial aspects of the Gap Analysis, as they identify issues in the mushroom production value chain and allow us to posit synergistic interactions that exist across different dimensions of the economy. We see the connection between these two sections as utilizing interventions that valorize waste products through different value-generating activities as the primary novel value generation capacity of this Gap Analysis in Denmark. That is, given the large waste-to-product ratio (around 5 to 1 for substrate to mushrooms) of mushroom production, and the incredibly large waste generation of society, finding synergistic solutions to the large waste generation capacities of both society and mushroom production is a means to begin to ‘close the loop’ of productive and consumptive activities. Although processing waste into substrate and growing mushrooms requires significant capital and infrastructure, it should be considered as a competitive option for at least a portion of waste utilization, especially in relation to existing strategies which rely primarily on incineration of waste. Emphasizing these suggested interventions can also have downstream consequences for the distribution of value associated with mushroom production, as it utilizes localized production and distribution networks.

One of the most important considerations for mushroom production, given contemporary issues of global climate change, which has anthropogenic causes directly associated with society’s metabolism of the earth and its ecosystems, is the narrative concerning waste generation and disposal for society at large, and more specifically mushroom waste generation and the potential for waste incorporation from other economic activities during the mushroom

production process. In this regard, there are many entry points for interventions to reduce the material footprint, the associated CO<sub>2</sub>e emissions, incorporating waste streams from other production endeavors, and reducing the downstream waste generation of mushroom production. These interventions operate around the context of continuing to produce high-quality mushrooms, but doing so using available waste sources from other economic activities, such as food production, shipping and packaging, and household and industry practices. The narrative of this Gap Analysis, which focuses on mushroom production, discusses using circular economic principles to produce high quality products while envisioning production activities that minimize waste generation and even go so far as to posit utilization of other waste streams generated in other economic activities.

For instance, Table 5 illustrates some points of entry for planned interventions as they are shown by the available data. Table 5 shows the amount of waste generated in three categories: industry and household LCW, crop residues from farming, and biowaste from industry and households (all values derived from Figures 1 and 2, and Tables 2 and 3; they are given as a 10% availability scenario). These existing waste flows are connected to substrate generation via a known industrial conversion ratio, which states that the initial quantity of waste has water and supplementation added to give a conversion ratio of around 2.25 kg of substrate per kg of waste input. In general, there is about a 20-25% (average 22.5%) conversion ratio of substrate material to mushrooms; we therefore incorporated this in our calculations, while only assuming a 10% uptake of existing waste streams, given the exigent competing uses, such as incineration, or animal feed for crop residues. These calculations were done for two types of mushrooms, primary decomposers such as oyster or shiitake, and secondary decomposers such as button mushrooms; the latter using composted biowaste as a substrate input, and the former using LCW, including crop residues, as their substrate input. Using just 10% of the existing waste streams from industry and household LCW and biowaste in Denmark produces a theoretical total of 515,250 tonnes of substrate; 10% of crop residues would produce 4,366,158 tonnes of substrate. The former would have a potential export value of 412,200,000 Euros, which includes the cost of producing it, with the later having a value of 3,493,800,000 Euros, which also includes the cost of production.

Table 5. Valorization potential of available waste as mushroom substrate source in Denmark. All values are in 1000 tonnes or 1000 Euros.

	Waste (tonnes)	Substrate Amount (tonnes)	Substrate cost (Euros)	Substrate Export Value (Euros)	Mush. Prod. (tonnes)	Agaricus Cost (Euros)	Agaricus value (Euros)	Oyster Cost (Euros)	Oyster Value (Euros)	Shiitake Cost (Euros)	Shiitake Value (Euros)	Total Value (Euros)	SMS Resid. (tonnes)	SMS to Compost (tonnes)
Industry + Household LCW (2012-2020)	105	236	-47,432	189,000	53			-64,034	947,574	-80,042	613,939	1,561,513	101	23

<b>Farming Crop Residue (2012-2019)</b>	1,941	4,366	-873,450	3,493,800	982			-1,178,863	1,7516,581	-1,473,578	11,349,096	28,865,677	1,862	419
<b>Biowaste Total (2011-2019)</b>	124	279	-55,800	223,200	63	-100,499	736,539					736,539	119	27

From this 10% total waste incorporation of Industry and Household LCW and biowaste waste conversion into substrate, approximately 116,000 tonnes of mushrooms could be produced. However, it should be mentioned that this value is 11.6 times the peak value of Danish domestic mushroom production in 2009. It is 29 times higher than Danish domestic production in 2017; furthermore, it is 11.5% of the total EU mushroom production from 2018. Using 10% of Danish-generated crop residues would allow for the production of 982,386 tonnes of mushrooms, which is around 95% of EU production. Therefore, this illustrates the massive production potential, but it is only given as a demonstration, as it would require massive additional infrastructure necessary for logistics around delivery; timely year-round supply of inputs; sanitation and treatment; production; and distribution. Furthermore, existing demand trends—currently around 12,000 tonnes a year in Denmark (Table 1)—shows that incorporating only around 1% of total Industry and Household LCW and biowaste in Denmark (around 23,000 tonnes of waste) would produce enough mushrooms to satisfy extant demands. Given that existing demand for mushroom consumption globally is increasing around 7% per year [73], and assuming that the infrastructure could be developed, the large potential for production could be used beyond this 1% for the export market.

Having done these production estimations for both mushroom types, we then used final market prices, averaged across the major four grocery stores in Denmark (Fotex, Netto, Rema 1000, and Lidl), and then subtracted a fixed estimate of general costs of production, to illustrate the potential value generation: we calculated that using 10% of industry and household LCW and biowaste would generate a total value of around 2,298,051,759 Euros. There are other distributional factors within this value to be considered, such as transportation, processing, and market capital depreciations, all of which would receive portions of this total value; however, we were not able to obtain this economic information from other stakeholders, given the highly competitive nature of the market. This value is therefore only a gross estimate of the entire economic activity and its valuation, and does not demonstrate the distribution of value to specific actors within the mushroom production value chain.

Table 5 also shows the associated waste generation of mushroom production in the form of SMS to demonstrate how many thousands of tonnes of soil amendment, for instance, could be used in place of fertilizer on agricultural fields or backyard gardens: we calculated that 220,000

tonnes of SMS from household and industrial biowaste and LCW waste, and 1,861,540 tonnes of SMS from crop residues were generated; this is only from 10% total uptake of the suggested waste streams. Tailoring production based on demand needs in Denmark (12,000 tonnes per year consumed) necessitates 1% utilization of LCW and biowaste, which would produce around 22,000 tonnes of SMS for soil amendment purposes. It should be noted that SMS is in some ways more advantageous in agriculture compared to conventional fossil-fuel based fertilizers, as its slow rate of release of latent nutrients avoids the major issues of eutrophication, while also being more advantageous to plants, who benefit from slower uptake [74]–[77]. Finally, we have calculated the ratio of SMS to compost in the last column of Table 5, which demonstrates that around 49,000 tonnes of compost can be produced from the input of 220,000 tonnes of SMS from our initial 10% uptake scenario of LCW and biowaste utilization. Overall, Table 5 demonstrates the connection between waste production in Denmark and potential utilization by using the lens of value generation. We have done this with an initial illustration scenario of 10% uptake, but 1% uptake is much more plausible; even just 1% uptake of LCW and biowaste streams would meet existing Danish demands for mushroom production. In the context of substrate import-reliant extant strategies in Denmark, this Gap Analysis has shown that there are areas of intervention that can create value with little diversion of waste streams to meet existing mushroom consumption needs in Denmark.

To compare this to Figure 3, which shows costs associated with waste disposal in Copenhagen, Denmark, Table 5 demonstrates that 1 tonne of incorporated LCW waste, for example, can be transformed into 2.25 tonnes of substrate; this can produce around 0.5 tonnes of Oyster mushrooms, which sells for around 13,000 Euros on average (26,000 Euros per tonne in Denmark on average). The costs associated with this value can only be estimated, and this value has embedded value distributions for processing, transport, refrigeration, marketing, and point of sale upkeep, just to name a few examples. This can be compared to the 765 DKK/tonne of waste (102 Euros/tonne), which is the average net cost per tonne of waste collected by the municipality seen in Figure 3. To be competitive, the price paid by substrate producers in Denmark would have to mirror the prices currently paid: 225 DKK/tonne for garden waste, 900 DKK/tonne for woody material, 2,500 DKK/tonne for cardboard, 300 DKK/tonne for food waste, and 1,000 DKK/tonne for paper. These values are more than what current users are charged (500 DKK/tonne for cardboard and 600 DKK/tonne for paper), as the municipality sells at a loss. The downstream value of these products is not known, as they are recycled into various products such as new boxes and packaging, or incinerated (as woody material is), or made into compost; however, it is clear that the embedded value of a tonne of waste has much potential as mushroom substrate, and eventually mushrooms, as the price of the final product is high. This

also assumes a wide distribution of value as well, as there are many moving sectors of activity in the mushroom production value chain.

It is also worth considering the mushroom production value chain as it extends beyond Table 5: namely, the downstream uses of spent mushroom substrate (SMS). We have already connected the generation of waste from sectors of the Danish economy at large and posited uses for these materials in mushroom production; however, it is also worth considering that this synergy is bi-directional. That is, only about 25% of the substrate for growing mushrooms is used in production. The remaining material (around 46%, given the degradation and loss of water), which is known as spent mushroom substrate (SMS) can be used as a soil amendment. Table 5 also shows the associated waste generation of mushroom production in the form of SMS to demonstrate how many thousands of tonnes of soil amendment, for instance, could be used in place of fertilizer on agricultural fields or backyard gardens. This intervention has been corroborated by our interviews; in one instance, an interviewee pointed out that they sent their SMS out as a soil amendment to organic farmers. SMS has been noted to be a very effective soil amendment that provides natural fertilizer at a very slow pace of release, which is critical for appropriate soil nutrient dynamics. Using more SMS would help reduce fertilizer pollution, downstream eutrophication, and would buffer against the rising price of natural gas (the primary input component for fertilizer creation) which is currently causing a global-scale crisis, with prices of fertilizer upwards of 1,000 USD per tonne which has caused some countries such as Brazil to struggle to fill orders [78]. Furthermore, current environmental regulations in Denmark, which aim to restrict the amount of fertilizer used on farmland to control the aforementioned issues, allow for much more extensive, almost unlimited, use of the legal category 'soil amendment'. SMS is a valuable soil amendment because it has a lot of carbon in it, mostly in the form of cellulose, which is degraded primarily after hemicellulose and lignin by mushrooms. The high level of carbon is compatible with the humus layer of the soil, as it improves soil moisture retention, rates of organic carbon, and retention of nutrients via steady state dynamics. In our interview, the participant noted that the only cost to the farmer is transportation, as the producer does not sell the SMS, but donates it. Another producer noted a similar pattern, but also stated that they saw the value of this fertilizer-replacement, and therefore intended to sell it in the future to farmers. There are other applications of SMS as well, such as turning it into compost, or using it for animal feed, as primary decomposers selectively degrade lignin and hemicellulose, often leaving cellulose which can be used by ruminants, or even other fungi, downstream [79], [80]. In summation, there are many novel points of intervention that are being investigated in Denmark that aim to connect the waste production of economic activities, such as agriculture, with mushroom production, whose waste in turn can be effectively cycled back to different agricultural applications, from animal feed to soil amendment.

These interventions are already being utilized by some value chain actors in Denmark, but their uptake is mostly occurring in small-scale producers, and there can be much benefit from discussing wider adoption of these practices.

#### 4.4 Mushroom Production Supply and Demand in Ireland

Table 6 demonstrates a summary of the mushroom production environment in Ireland. A more thorough description and accounting can be seen in *Deliverable 1.1: Mushroom Value Chain Analysis*. In general, from 1991-2019, Ireland produced on average 59,690 tonnes of mushrooms per year, at a cost of 1,755 Euros/tonne, for a total cost of 104,742,029 Euros/year. Ireland had a positive demand gap, as they produced more than they consumed with a value of 20,741 tonnes (59,690-38,949 tonnes). Ireland had a positive trade balance, importing only 11,479 tonnes/year, and exporting 32,220 tonnes/year, leaving a positive balance of 20,741 tonnes/year on average for 2010-2019. This was sold on the market for approximately 74,298,506 Euros/year.

Table 6. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Ireland. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities.

COUNTRY	CATEGORIES	IMPORT	EXPORT	LOCAL DEMAND GAP	LOCAL PRODUCTION	LOCAL CONSUMPTION	DEMAND GAP
IRELAND	<i>Data Range</i>	<i>(Average for 2005-2019)</i>					
	Mushroom (tonnes/year)	11,479	32,220	20,741	59,690	38,949	20,741
	Monetary value (Euros/year)	21,964,900	96,263,406	74,298,506	104,742,029	346,642,141	
	Price per tonne (Euros/tonne)	1,945	3,474		1,755	8,900	

#### 4.5 Relevant Waste Sourcing for Mushroom Production in Ireland

Table 7 demonstrates the different types of crop residues that are estimated to have been generated in Ireland from 2010 to 2016. This information is derived from a paper by Bedoic, Cosic, and Duic (2019) [62], who used different models to calculate the amount of crop residues that were generated in each year for all the countries in the EU. They also have data on Fruit, Vegetable, and Animal products as well; for the purposes of this deliverable, we have only used the Cereal category, as this is of the highest relevance for use as inputs for mushroom production substrate. Similar to Denmark, Ireland’s highest sources of crop residues comes from Barley

straw (with an average of 1.75 million tonnes) and Wheat straw (with an average of 966,000 tonnes).

Table 7. Lignocellulosic and Crop Residue Waste Generation for Cereals in Ireland from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes.

	2010	2011	2012	2013	2014	2015	2016	MIN	MAX	AVG
BARLEY STRAW	1,431,487	1,648,208	1,454,155	1,951,134	2,036,058	2,019,905	1,708,146	1,431,487	2,036,058	1,749,870
BARLEY BRAN	464,189	442,506	422,646	578,581	537,460	517,220	467,545	422,646	578,581	490,021
BARLEY HULL	391,660	373,365	356,608	488,178	453,482	436,404	394,491	356,608	488,178	413,455
CORN STALK	0	0	0	0	0	0	0	0	0	0
CORN HUSK	0	0	0	0	0	0	0	0	0	0
CORN COB	0	0	0	0	0	0	0	0	0	0
CORN BRAN	47,297	36,849	57,672	102,638	121,741	121,558	127,759	36,849	127,759	87,931
TRITICALE STRAW	0	0	0	0	0	0	0	0	0	0
TRITICALE BRAN	12	45	5	0	0	12	4	0	45	11
OAT STRAW	189,436	214,346	198,079	247,726	193,067	253,059	233,093	189,436	253,059	218,401
OAT BRAN	18,621	15,047	15,647	24,645	17,383	16,297	21,564	15,047	24,645	18,458
OAT HULL	36,001	29,091	30,252	47,646	33,608	31,507	41,690	29,091	47,646	35,685
RICE STRAW	0	0	0	0	0	0	0	0	0	0
RICE BRAN	434	159	212	148	481	770	770	148	770	425
RICE HUSK	1,129	412	552	386	1,251	2,003	2,002	386	2,003	1,105
ROTTEN RICE	4,299	4,319	4,331	4,339	4,352	4,374	4,466	4,299	4,466	4,354
RYE STRAW	0	0	0	0	0	0	0	0	0	0
RYE BRAN	754	187	116	4	5	10	35	4	754	158
WHEAT STRAW	922,219	1,255,766	944,957	755,770	977,112	940,910	878,760	755,770	1,255,766	966,122
WHEAT BRAN	149,471	164,787	154,719	119,841	147,333	130,513	143,316	119,841	164,787	144,283

#### 4.6 Mushroom Production Supply and Demand in Hungary

Table 8 demonstrates a summary of the mushroom production environment in Hungary. A more thorough description and accounting can be seen in *Deliverable 1.1: Mushroom Value Chain Analysis*. From 2010-2020, Hungary produced on average 21,997 tonnes of mushrooms per year, at a cost of 1,200 Euros/tonne, for a total cost of 26,396,400 Euros/year. Hungary had a positive demand gap, as they produced more than they consumed with a value of 13,155 tonnes/year (21,997-8,842 tonnes). For Hungary, data exist only for the volumes of imports and exports, not

the prices; this showed that Hungary also had a positive trade balance of 13,155 tonnes/year on average from 2010-2020.

Table 8. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Hungary. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities.

COUNTRY	CATEGORIES	IMPORT	EXPORT	LOCAL DEMAND GAP	LOCAL PRODUCTION	LOCAL CONSUMPTION	DEMAND GAP
HUNGARY	<i>Data Range</i>	<i>(Average for 2010-2020)</i>					
	Mushroom (tonnes/year)	2,334	15,489	13,155	21,997	8,842	13,155
	Monetary value (Euros/year)	ND	ND	ND	26,396,400	18,213,513	
	Price per tonne (Euros/tonne)	ND	ND	ND	1,200	2,060	

### 4.7 Relevant Waste Sourcing for Mushroom Production in Hungary

Figure 4 shows the Industry and Household Waste Components over time from 2012-2020 for Hungary. For each year, industry is on the left (in red/orange), with household values on the right (blue/green). Industry wood category includes the industrial wooden packaging plus wastes of wood processing, furniture manufacturing and pulp & paper industries. These values were derived from the “Hungarian Statistical Office” (KSH) and “National Environmental Protection Information System” (Országos Környezetvédelmi Információs Rendszer, OKIR). Overall, they show that Industry produces around 14 times more waste than households in Hungary over the time period of 2012 to 2020.

Figure 4. Industry and Household Waste Components over time from 2012-2020 in Hungary. For each year, industry is on the left (in red/orange), with household values on the right (blue/green).

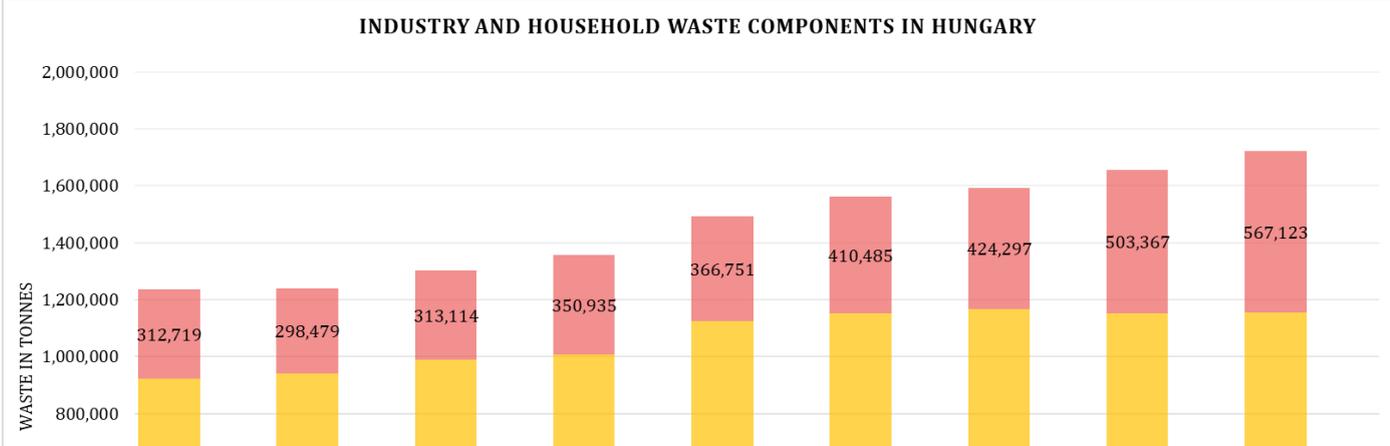


Figure 5 shows biowaste production from household and industry in Hungary from 2011-2020 in tonnes. Biowaste from industry includes the wastes of aquaculture, agriculture, horticulture, forestry and food processing. In the statistical categorization biodegradation is not an aspect, thus biodegradability and applicability from the point of oyster mushroom production are sole assumptions. Some specific examples of the materials otherwise considered unsuitable for consumption or processing are plant-tissue waste, wastes from forestry, wastes from spirits distillation, and wastes not otherwise specified. These values were derived from the “Hungarian Statistical Office” (KSH) and “National Environmental Protection Information System” (Országos Környezetvédelmi Információs Rendszer, OKIR). Unlike Figure 4, Figure 5 has a much closer ratio of waste produced by industry compared to households in Hungary.

Figure 5. Biowaste production and lifecycle as generated from household and industry in Hungary from 2011-2019 in tonnes.

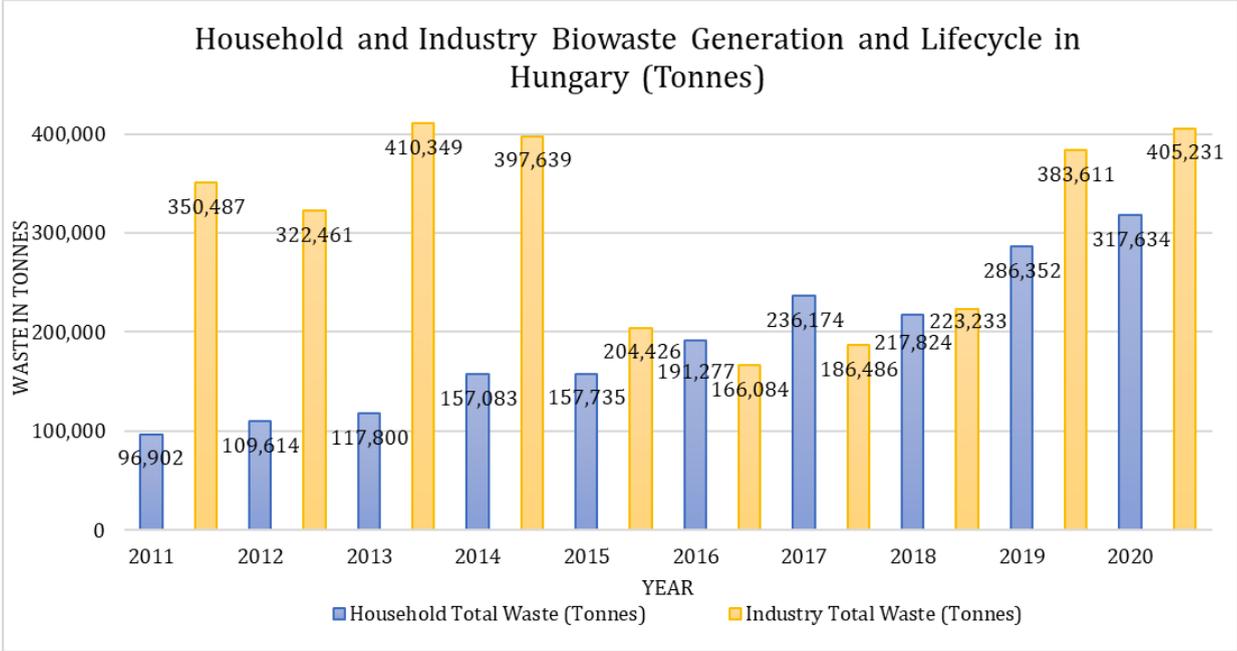


Table 9 details information about the amount of cereal waste component generation in Hungary. The values in Table 9 were derived from a paper by Bedoic, Cosic, and Duic (2019) [62]. These materials have high usability for valorization via use as mushroom substrate. Their changes over time can be seen as useful indicators detailing the availability of substrate input materials for downstream mushroom production. Unlike Ireland and Denmark, the top crop residue source stems from Corn Stalks in Hungary, at around 17.3 million tonnes per year on average. Consistent with Denmark and Ireland, however, the second highest was Wheat Straw, at around 6.6 million tonnes on average.

Table 9. Lignocellulosic and Crop Residue Waste Generation for Cereals in Hungary from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes.

	2010	2011	2012	2013	2014	2015	2016	MIN	MAX	AVG
<b>BARLEY STRAW</b>	1,144,763	1,197,918	1,208,190	1,288,100	1,555,146	1,718,443	1,944,961	1,144,763	1,944,961	1,436,789
<b>BARLEY BRAN</b>	209,614	168,893	243,036	208,827	271,216	205,614	316,378	168,893	316,378	231,940
<b>BARLEY HULL</b>	176,862	142,504	205,061	176,197	228,839	173,487	266,944	142,504	266,944	195,699
<b>CORN STALK</b>	16,499,724	18,879,829	11,250,519	15,960,109	22,133,671	15,760,186	20,743,192	11,250,519	22,133,671	17,318,176
<b>CORN HUSK</b>	1,725,913	1,974,878	1,176,833	1,669,468	2,315,238	1,648,555	2,169,790	1,176,833	2,315,238	1,811,525
<b>CORN COB</b>	3,520,862	4,028,750	2,400,738	3,405,714	4,723,085	3,363,052	4,426,372	2,400,738	4,723,085	3,695,510
<b>CORN BRAN</b>	401,590	566,456	63,952	605,105	916,140	318,926	812,221	63,952	916,140	526,341
<b>TRITICALE STRAW</b>	911,725	859,300	857,725	1,140,950	1,216,125	1,255,775	1,201,075	857,725	1,255,775	1,063,239
<b>TRITICALE BRAN</b>	56,503	53,740	52,424	70,239	74,762	75,312	71,395	52,424	75,312	64,911
<b>OAT STRAW</b>	157,035	172,043	182,709	175,312	181,744	172,418	138,878	138,878	182,709	168,591
<b>OAT BRAN</b>	16,725	18,546	19,816	19,103	19,642	18,152	14,746	14,746	19,816	18,104
<b>OAT HULL</b>	32,334	35,855	38,311	36,933	37,975	35,094	28,509	28,509	38,311	35,002
<b>RICE STRAW</b>	7,598	11,365	14,216	10,888	10,217	12,139	13,893	7,598	14,216	11,070
<b>RICE BRAN</b>	1,153	1,868	1,306	362	704	2,662	2,880	362	2,880	1,562
<b>RICE HUSK</b>	2,997	4,858	3,395	940	1,831	6,922	7,489	940	7,489	4,062
<b>ROTTEN RICE</b>	5,137	5,123	5,095	5,083	5,067	5,056	5,043	5,043	5,137	5,086
<b>RYE STRAW</b>	114,463	104,516	0	0	139,113	150,728	121,902	0	150,728	90,103
<b>RYE BRAN</b>	8,939	8,275	0	0	9,601	11,735	9,805	0	11,735	6,908
<b>WHEAT STRAW</b>	5,361,710	5,879,174	5,742,245	7,241,602	7,577,122	7,677,259	8,068,579	5,361,710	7,677,259	6,579,852
<b>WHEAT BRAN</b>	287,307	493,543	463,773	457,334	535,896	629,365	554,756	287,307	629,365	488,853

For Hungary, detailed information about waste collection costs was not available. However, general costs for disposal of non-hazardous municipal waste were shown to be around 23,749 HUF per tonne of waste. For disposal of biowaste (in general for composting), the cost was 12,700 HUF per tonne of waste. These values are derived from the FKF, which is the Waste Management Utility of Budapest Municipality (<https://www.fkf.hu/dijszabasok/hulladek-artalmatlanitasi-dijak>). Currently, there is a bag based system for biowaste collection. Using special bags provided by FKF, biowaste can be placed next to the bins and taken by FKF. These services are free for households with a valid contract for waste management. Dedicated bins for paper are also available for households and emptied with weekly frequency for free. It was noted that different fees apply for industry, but

details were not collected. They are noted to be set by participating companies on the market, and not by utility.

Table 10 details the connection between the amount of waste generation in Hungary, and the potential greenhouse gas emissions associated with its disposal or degradation. These values were estimated using the resources listed in the bottom of the table.

Table 10. Supply of waste available for mushroom production and associated greenhouse gas emissions in Hungary.

Waste (average 2012-2020)	Source from	Paper	Wood	Crop Residues	Biodegradable waste	Total	Proportional Incineration (25%)
Industry waste)	(tonnes waste)	1,067,997	394,141	33,966,403	293,864	35,722,405	
Household waste)	(tonnes waste)	89,756	2,591	0	188,840	281,187	
GHG emissions (tonnes CO <sub>2</sub> e/tonne waste)		0.94 [65], [66]	1.65-1.8 [67]	1.30 [68]	2.54 [69]		
Potential emissions	GHG	1,088,288	684,364	44,156,324	1,226,067	47,155,042	11,788,761
Lignocellulosic content (%)		87.25 % [70]	95.00% [71]	97.5% [72]	35.83%		

#### 4.8 Mushroom Production Supply and Demand in Romania

Table 11 demonstrates a summary of the mushroom production environment in Romania. A more thorough description and accounting can be seen in *Deliverable 1.1: Mushroom Value Chain Analysis*. From 2012-2020, Romania produced on average 12,460 tonnes of mushrooms per year, at a cost of 1,250 Euros/tonne, for a total cost of 15,582,500 Euros/year. Romania had a positive demand gap, as they produced more than they consumed with a value of 5,423 tonnes/year (12,466-7,043 tonnes). Romania also had a positive trade balance, with 4,493 tonnes/year more mushrooms being exported than were imported on average from 2013-2020.

Table 11. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Romania. Values are averages of the listed years in the 'Data Range' rows above their corresponding activities.

COUNTRY	CATEGORIES	IMPORT	EXPORT	LOCAL DEMAND GAP	LOCAL PRODUCTION	LOCAL CONSUMPTION	DEMAND GAP
ROMANIA	<i>Data Range</i>	<i>(Average for 2013-2020)</i>	<i>(Average for 2013-2020)</i>	<i>(Average for 2013-2020)</i>	<i>(Average for 2012-2020)</i>	<i>(Average for 2013-2020)</i>	<i>(Average for 2013-2020)</i>
	Mushroom (tonnes/year)	2,464	6,957	4,493	12,466	7,043	5,423
	Monetary value (Euros/year)	3,080,000	8,695,825	5,615,825	15,582,500	8,803,365	

	Price per tonne (Euros/tonne)	1,250	1,250	1,250	1,250	
--	-------------------------------	-------	-------	-------	-------	--

### 4.9 Relevant Waste Sourcing for Mushroom Production in Romania

As you can see in Figure 6, the total industry generation of lignocellulosic waste (LCW)—paper, cardboard, and woody material—in 2020 in Romania was 748,973 tonnes, while for households it was 1,285,801 tonnes. The total waste generation for these two categories in 2020 was therefore 2,034,774 tonnes. This figure also shows that for industry, the largest (by weight) waste generation category was cardboard; for household, it was all 3 categories. In general, in Romania, over this time period, industry generated only 62% of the amount of household waste.

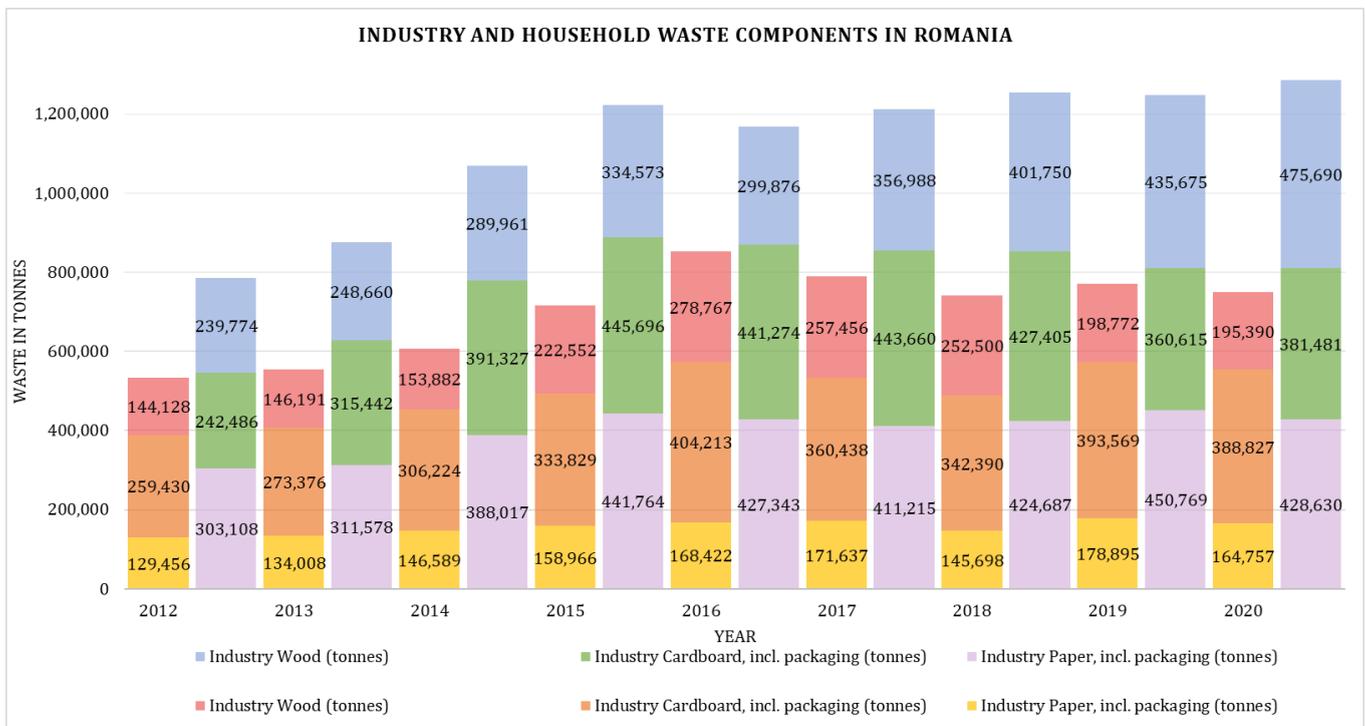


Figure 6. Industry and Household Waste Components over time from 2012-2020 in Romania. For each year, industry is on the left (in red/orange), with household values on the right (blue/green).

Figure 7 shows that, in 2018, Romanian industry produced 466,465 tonnes of biowaste, with approximately 370,062 tonnes of saved waste (46.28% of total biowaste) being used for energy generation via incineration. The figure also shows that in the industry it is a fairly high incineration ratio.

Figure 7. Biowaste production and lifecycle as generated from household and industry in Romania from 2011-2019 in metric tonnes.

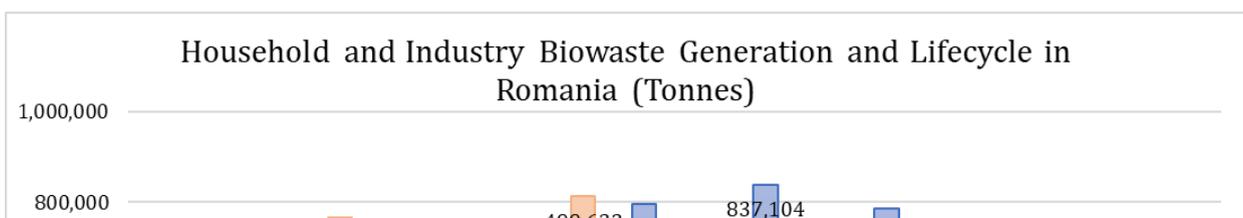


Table 12 demonstrates the different types of crop residues that are estimated to have been generated in Romania from 2010 to 2016. This information is derived from a paper by Bedoic, Cosic, and Duic (2019) [62], who used different models to calculate the amount of crop residues that were generated in each year for all the countries in the EU. They also have data on Fruit, Vegetable, and Animal products as well; for the purposes of this deliverable, we have only used the Cereal category, as this is of the highest relevance for use as inputs for mushroom production substrate. Similar to Hungary, the highest source of crop residue was Corn Stalks, with an average value of around 23.8 million tonnes; the second highest is Wheat Straw, which is consistent with the other three countries at 9.87 million tonnes on average.

*Table 12. Lignocellulosic and Crop Residue Waste Generation for Cereals in Romania from 2010 to 2016. Data derived from Bedoic, Cosic, and Duic (2019) [62]. All values in tonnes.*

	2010	2011	2012	2013	2014	2015	2016	MIN	MAX	AVG
<b>BARLEY STRAW</b>	1,599,469	1,622,222	1,203,359	1,881,545	2,089,262	1,984,123	2,217,069	1,203,359	2,217,069	1,799,578
<b>BARLEY BRAN</b>	201,613	240,934	139,619	202,262	143,307	127,027	315,746	127,027	315,746	195,787
<b>BARLEY HULL</b>	170,111	203,288	117,803	170,659	120,915	107,179	266,410	107,179	266,410	165,195
<b>CORN STALK</b>	21,610,452	28,005,040	14,228,507	27,019,189	28,652,635	21,561,146	25,683,872	14,228,507	28,652,635	23,822,977
<b>CORN HUSK</b>	2,260,508	2,929,398	1,488,338	2,826,275	2,997,138	2,255,350	2,686,598	1,488,338	2,997,138	2,491,943
<b>CORN COB</b>	4,611,435	5,975,971	3,036,209	5,765,601	6,114,161	4,600,914	5,480,659	3,036,209	6,114,161	5,083,564
<b>CORN BRAN</b>	964,352	1,271,505	569,165	1,086,269	1,137,604	612,216	1,025,777	569,165	1,271,505	952,412
<b>TRITICALE STRAW</b>	307,800	362,000	334,825	612,575	688,050	662,725	718,325	307,800	718,325	526,614
<b>TRITICALE BRAN</b>	19,935	22,794	19,784	36,007	40,486	41,063	43,567	19,784	43,567	31,948
<b>OAT STRAW</b>	407,976	503,652	454,260	500,865	511,384	466,293	511,022	407,976	511,384	479,351
<b>OAT BRAN</b>	45,613	56,176	50,591	55,835	57,074	52,166	56,889	45,613	57,074	53,478
<b>OAT HULL</b>	88,186	108,607	97,809	107,948	110,342	100,854	109,985	88,186	110,342	103,390
<b>RICE STRAW</b>	78,535	83,218	64,861	69,686	57,586	63,468	55,638	57,586	83,218	69,559
<b>RICE BRAN</b>	1,161	5,149	986	2,195	2,517	3,646	2,520	986	5,149	2,596
<b>RICE HUSK</b>	3,018	13,387	2,562	5,707	6,544	9,480	6,552	2,562	13,387	6,750
<b>ROTTEN RICE</b>	15,891	15,816	15,735	15,676	15,619	15,559	15,472	15,472	15,891	15,681
<b>RYE STRAW</b>	49,706	45,501	26,448	34,525	35,322	35,264	37,599	26,448	49,706	37,766
<b>RYE BRAN</b>	4,381	3,948	2,203	3,034	3,208	3,265	3,471	2,203	4,381	3,359
<b>WHEAT STRAW</b>	8,369,006	10,269,490	7,628,760	10,506,773	10,922,126	11,465,885	12,140,827	7,628,760	11,465,885	9,860,340
<b>WHEAT BRAN</b>	688,776	1,040,739	597,505	544,494	559,349	860,099	448,312	448,312	1,040,739	677,039

Table 13 details the connection between the amount of waste generated and the associated estimated greenhouse gas emissions. These estimations were derived from the sources listed at the bottom of the table. The total average values from 2012-2020 for industry and household categories have been shown for each specific LCW, crop residue, and biowaste category (e.g. Figures 1 and 2). As is consistent with the other countries, crop residues is far higher than the other categories.

Table 13. Supply of waste available for mushroom production and associated greenhouse gases in Romania.

Waste (average 2012-2020)	Source from	Paper	Cardboard	Wood	Crop Residues	Biodegradable waste	Total	Proportional Incineration (25%)
Industry waste)	(tonnes waste)	155,381	340,255	205,515	26,047,968	1,118,058	27,867,177	
Household waste)	(tonnes waste)	398,568	383,265	342,550	0	1,047,692	2,172,075	
GHG emissions (tonnes CO <sub>2</sub> e/tonne waste)		0.94 [65]	0.94 [66]	1.65-1.8 [67]	1.30 [68]	2.54 [69]		
Potential GHG emissions		520,712	694,579	945,412	33,862,358	5,501,005	41,524,067	10,381,017
Lignocellulosic content (%)		87.25 % [70]	83.8 % [70]	95.00% [71]	97.5% [72]	35.83%		

## 5 Conclusions

The MUSHNOMICS *Deliverable 1.3: Gap Analysis* has tabulated and demonstrated the amount of different waste sources in the four consortium countries (Denmark, Hungary, Ireland, and Romania) that are potentially useful as mushroom production inputs. Namely, Lignocellulosic Waste (LCW) such as paper, cardboard, wood, and crop residues, and biowaste such as garden waste and kitchen scraps. These waste sources have different use-pathways: LCW is useful for primary decomposers such as Oyster mushrooms, while biowaste must first be composted and prepared before use for substrate for secondary decomposers such as Button Mushrooms. We have shown here, where data were available, the amount of waste generated in each country per category per year, as well as the cost of disposing the waste, and the associated greenhouse gas emissions of their disposal. Knowing this information has allowed us to hypothesize potential interventions involving the use of these different ‘waste’ streams for valorization into mushroom products. We have also taken market information, where available, and used this to show how much value there is per tonne of mushroom produced, and compared this to the cost of disposing a tonne of different ‘waste’ sources. In summation, we have shown that there is much room for synergies across economic sectors in all four countries that can

valorize 'waste' into useful mushroom substrate inputs. This can be done, for example, via the agricultural sector supplying widely available crop residues, such as Wheat Straw, for mushroom substrate inputs; downstream, the agricultural sector can in turn benefit from spent mushroom substrate being used as a returned product in the form of soil amendment or crop feed component. The *Deliverable 1.3: Gap Analysis* has demonstrated and discussed the value of these different interventions and connections between different sectors of the economy within the context of mushroom production. This is of crucial importance for countries such as Denmark, which doesn't have any industrial producers of mushroom substrate: both complete substrate products, and many substrate components are imported from other countries, even for those who assemble the substrate domestically (wood pellets, saw dust, etc.). Furthermore, Denmark imports around 45% of the mushrooms that are consumed domestically. Using domestic sources of substrate inputs can reduce greenhouse gas emissions associated with transport and hopefully also increase localized production of mushrooms as well. Ideally, considering that all four countries produce over 20 million tonnes of crop residues, there is room for extant waste streams to be incorporated and valorized into mushroom production activities and improve respective overall waste generation and disposal dynamics.

## **6 Acknowledgements**

MUSHNOMICS is part of the ERA-NET Cofund ICT-AGRI-FOOD, with funding provided by national funding body in Denmark [Green Development and Demonstration Program under The Ministry of Food, Agriculture and Fisheries of Denmark within the framework of MUSHNOMICS project, journal number: 34009-20-1815), Hungary (National Research, Development and Innovation Office), Ireland (Department of Agriculture, Food and the Marine (DAFM) and Romania (Romanian National Authority for Scientific Research and Innovation Funding) and co-funded by the European Union's Horizon 2020 research and innovation program, Grant Agreement number 862665.

## **7 References**

- [1] A. Antonelli *et al.*, "State of the World's Plants and Fungi 2020," p. 100, 2020, doi: doi.org/10.34885/172.
- [2] A. E. Rodriguez Estrada, M. del M. Jimenez-Gasco, and D. J. Royse, "Improvement of yield of *Pleurotus eryngii* var. *eryngii* by substrate supplementation and use of a casing overlay," *Bioresource Technology*, vol. 100, no. 21, pp. 5270–5276, 2009, doi: 10.1016/j.biortech.2009.02.073.
- [3] C. H. Liang, C. Y. Wu, P. L. Lu, Y. C. Kuo, and Z. C. Liang, "Biological efficiency and nutritional value of the culinary-medicinal mushroom *Auricularia* cultivated on a sawdust basal substrate supplement with different proportions of grass plants," *Saudi Journal of Biological Sciences*, vol. 26, no. 2, pp. 263–269, Feb. 2019, doi: 10.1016/J.SJBS.2016.10.017.
- [4] C. Xie, W. Gong, L. Yan, Z. Zhu, Z. Hu, and Y. Peng, "Biodegradation of ramie stalk by *Flammulina velutipes*: mushroom production and substrate utilization," *AMB Express*, vol. 7, no. 1, 2017, doi: 10.1186/s13568-017-0480-4.
- [5] V. Kleofas, L. Sommer, M. A. Fraatz, H. Zorn, and M. Rühl, "Fruiting Body Production and Aroma Profile Analysis of *Agrocybe aegerita* Cultivated on Different Substrates," *Natural Resources*, vol. 05, no. 06, pp. 233–240, 2014, doi: 10.4236/nr.2014.56022.
- [6] K. Yamanaka, "Cultivation of Mushrooms in Plastic Bottles and Small Bags," *Edible and Medicinal Mushrooms*, pp. 309–338, Aug. 2017, doi: 10.1002/9781119149446.CH15.
- [7] A. Pardo-Giménez, J. E. Pardo González, and D. C. Zied, "Casing Materials and Techniques in *Agaricus bisporus* Cultivation," *Edible and Medicinal Mushrooms*, pp. 149–174, 2017, doi: 10.1002/9781119149446.ch7.
- [8] A. Pardo - Gimenez, J. E. Pardo - González, and D. Cunha Zied, "Supplementation of High Nitrogen *Agaricus* Compost: Yield and Mushroom Quality," Jan. 2018, Accessed: Dec. 02, 2021. [Online]. Available: <http://localhost/xmlui/handle/123456789/3560>

- [9] M. A. Kabel, E. Jurak, M. R. Mäkelä, and R. P. de Vries, "Occurrence and function of enzymes for lignocellulose degradation in commercial *Agaricus bisporus* cultivation," *Applied Microbiology and Biotechnology*, vol. 101, no. 11, pp. 4363–4369, 2017, doi: 10.1007/s00253-017-8294-5.
- [10] A. M. Vos *et al.*, "H<sub>2</sub>O<sub>2</sub> as a candidate bottleneck for mnp activity during cultivation of *agaricus bisporus* in compost," *AMB Express*, vol. 7, no. 1, pp. 1–9, 2017, doi: 10.1186/s13568-017-0424-z.
- [11] R. Yadav, "Use of vermiproducts in the cultivation of milky mushroom (*Calocybe indica*)," 2006, Accessed: Dec. 02, 2021. [Online]. Available: <https://krishikosh.egranth.ac.in/handle/1/80665>
- [12] D. J. Royse, J. Baars, and Q. Tan, "Current Overview of Mushroom Production in the World," *Edible and Medicinal Mushrooms*, pp. 5–13, Aug. 2017, doi: 10.1002/9781119149446.CH2.
- [13] K. J. (ed.) Willis, "State of the World's Fungi 2018," *Royal Botanic Gardens. Kew*, 2018.
- [14] Y. Ma, Q. Wang, X. Sun, X. Wang, W. Su, and N. Song, "A Study on recycling of spent mushroom substrate to prepare chars and activated carbon," *BioResources*, vol. 9, no. 3, pp. 3939–3954, 2014, doi: 10.15376/biores.9.3.3939-3954.
- [15] H. Sardar *et al.*, "Effect of different agro-wastes, casing materials and supplements on the growth, yield and nutrition of milky mushroom (*Calocybe indica*)," *Folia Horticulturae*, vol. 32, no. 1, pp. 115–124, 2020, doi: 10.2478/fhort-2020-0011.
- [16] S. T. Chang, "Potential for Application in B Razil," vol. 19, pp. 33–34, 2007.
- [17] K. A. Subbiah and V. Balan, "A comprehensive review of tropical milky white mushroom (*Calocybe indica* P&C)," *Mycobiology*, vol. 43, no. 3, pp. 184–194, 2015, doi: 10.5941/MYCO.2015.43.3.184.
- [18] R. Amin, A. Khair, N. Alam, and T. S. Lee, "Effect of Different Substrates and Casing Materials on the Growth and Yield of *Calocybe indica*," *Mycobiology*, vol. 38, no. 2, p. 97, 2010, doi: 10.4489/myco.2010.38.2.097.
- [19] H. Sardar *et al.*, "Agro-industrial residues influence mineral elements accumulation and nutritional composition of king oyster mushroom (*Pleurotus eryngii*)," *Scientia Horticulturae*, vol. 225, no. July, pp. 327–334, 2017, doi: 10.1016/j.scienta.2017.07.010.
- [20] H. T. Hoa, C. L. Wang, and C. H. Wang, "The effects of different substrates on the growth, yield, and nutritional composition of two oyster mushrooms (*Pleurotus ostreatus* and *Pleurotus cystidiosus*)," *Mycobiology*, vol. 43, no. 4, pp. 423–434, 2015, doi: 10.5941/MYCO.2015.43.4.423.
- [21] L. Marlina, S. Sukotjo, and S. Marsudi, "Potential of Oil Palm Empty Fruit Bunch (EFB) as Media for Oyster Mushroom, *Pleurotus ostreatus* Cultivation," *Procedia Chemistry*, vol. 16, pp. 427–431, 2015, doi: 10.1016/j.proche.2015.12.074.
- [22] A. Tesfaw, A. Tadesse, and G. Kiros, "Optimization of oyster (*Pleurotus ostreatus*) mushroom cultivation using locally available substrates and materials in Debre Berhan, Ethiopia," *Journal of Applied Biology & Biotechnology*, vol. 3, no. 01, pp. 15–20, 2015, doi: 10.7324/jabb.2015.3103.
- [23] O. M. Adedokun, "Oyster mushroom: Exploration of additional agro-waste substrates in Nigeria," *International Journal of Agricultural Research*, vol. 9, no. 1, pp. 55–59, 2014, doi: 10.3923/rjar.2014.55.59.
- [24] N. F., "Correlation of stipe length, pileus width and stipe girth of oyster mushroom (*Pleurotus ostreatus*) grown in different farm substrates," *Journal of Agricultural Biotechnology and Sustainable Development*, vol. 5, no. 3, pp. 54–60, 2013, doi: 10.5897/jabsd2013.0197.
- [25] "Eurostat - Data Explorer." [https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro\\_cpsh1&lang=en](https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_cpsh1&lang=en) (accessed Dec. 02, 2021).
- [26] F. Antunes *et al.*, "Value-Added Compounds and Potential Applications," *Molecules*, vol. 1, no. 25, pp. 1–40, 2020.

- [27] “Scientists unearth the secrets of mushroom compost | Euronews.”  
<https://www.euronews.com/next/2019/12/16/scientists-unearth-the-secrets-of-mushroom-compost> (accessed Dec. 01, 2021).
- [28] “Smart Mushroom: smart management of spent mushroom compost | Mushroom Forum.”  
<https://www.gombaforum.hu/en/2021/technologia/smart-mushroom-a-letermett-gombakomposzt-kezelese-okosan/> (accessed Dec. 01, 2021).
- [29] “What a Waste 2.0.”
- [30] “Statistics | Eurostat.”  
[https://ec.europa.eu/eurostat/databrowser/explore/all/envir?lang=en&display=list&sort=category&extractionId=PROJ\\_19NP\\_custom\\_1110748](https://ec.europa.eu/eurostat/databrowser/explore/all/envir?lang=en&display=list&sort=category&extractionId=PROJ_19NP_custom_1110748) (accessed Jul. 08, 2022).
- [31] “Statistics | Eurostat.”  
<https://ec.europa.eu/eurostat/databrowser/view/ten00108/default/table?lang=en> (accessed Jul. 08, 2022).
- [32] “Greenhouse Gas Inventory Data - Time Series - Annex I.” [https://di.unfccc.int/time\\_series](https://di.unfccc.int/time_series) (accessed Jul. 08, 2022).
- [33] J. D. Ward, P. C. Sutton, A. D. Werner, R. Costanza, S. H. Mohr, and C. T. Simmons, “Is Decoupling GDP Growth from Environmental Impact Possible?,” *PLOS ONE*, vol. 11, no. 10, p. e0164733, Oct. 2016, doi: 10.1371/JOURNAL.PONE.0164733.
- [34] N. J. Hagens, “Economics for the future – Beyond the superorganism,” *Ecological Economics*, vol. 169, p. 106520, Mar. 2020, doi: 10.1016/J.ECOLECON.2019.106520.
- [35] H. Haberl *et al.*, “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights,” *Environmental Research Letters*, vol. 15, no. 6, p. 065003, Jun. 2020, doi: 10.1088/1748-9326/AB842A.
- [36] J. Hickel and G. Kallis, “Is Green Growth Possible?,” <https://doi.org/10.1080/13563467.2019.1598964>, vol. 25, no. 4, pp. 469–486, Jun. 2019, doi: 10.1080/13563467.2019.1598964.
- [37] “Andrew McAfee and the Myth of America’s Green Growth.”  
<https://foreignpolicy.com/2020/06/18/more-from-less-green-growth-environment-gdp/> (accessed Jul. 08, 2022).
- [38] J. Hickel, *Less is more: How degrowth will save the world*. 2020. Accessed: Jul. 08, 2022. [Online]. Available:  
<https://books.google.com/books?hl=en&lr=&id=mLbIDwAAQBAJ&oi=fnd&pg=PT7&dq=less+is+more,+hickel&ots=nf6UsS3iRj&sig=Sf88TEZ72IDPMG4OcBb1qurX4EE>
- [39] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. K.-N. energy, and undefined 2018, “A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies,” *nature.com*, Accessed: Jul. 08, 2022. [Online]. Available:  
[https://idp.nature.com/authorize/casa?redirect\\_uri=https://www.nature.com/articles/s41560-018-0172-6&casa\\_token=i2YNdancH9gAAAAA:28qXP7pNpy97ka6hQ4MNZTiNMf\\_f71DLmPhrUycJZQWgTb20WrEdH6iwS4HQntoaVc0Ag7A5yPMwK-Gz](https://idp.nature.com/authorize/casa?redirect_uri=https://www.nature.com/articles/s41560-018-0172-6&casa_token=i2YNdancH9gAAAAA:28qXP7pNpy97ka6hQ4MNZTiNMf_f71DLmPhrUycJZQWgTb20WrEdH6iwS4HQntoaVc0Ag7A5yPMwK-Gz)
- [40] “Trends in Solid Waste Management.”  
[https://datatopics.worldbank.org/what-a-waste/trends\\_in\\_solid\\_waste\\_management.html](https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html) (accessed Jul. 08, 2022).
- [41] A. Chaabane, A. Ramudhin, M. P.-I. journal of production, and undefined 2012, “Design of sustainable supply chains under the emission trading scheme,” *Elsevier*, Accessed: Jul. 08, 2022. [Online]. Available:  
[https://www.sciencedirect.com/science/article/pii/S0925527310004184?casa\\_token=PufD\\_N](https://www.sciencedirect.com/science/article/pii/S0925527310004184?casa_token=PufD_N)

HZqdwAAAAA:MUcbWAUWCpG2veVMeG0tAZpETY4xTxWUnOWyShq8GC7c3ljicgJx8ZTPl\_N8w  
OeEzNQbn6I7YA

- [42] T. Paksoy, T. Bektaş, E. Ö.-T. R. P. E. Logistics, and undefined 2011, "Operational and environmental performance measures in a multi-product closed-loop supply chain," *Elsevier*, Accessed: Jul. 08, 2022. [Online]. Available: [https://www.sciencedirect.com/science/article/pii/S1366554510001213?casa\\_token=C\\_Yx8W\\_k5t4AAAAA:gMJ0T\\_qAPTpZ3CW-4sRcGLrjYpu3OgWDZilMYe7arsN8VQ-fFtwqBiD5xosgdSp66ex44BbgnA](https://www.sciencedirect.com/science/article/pii/S1366554510001213?casa_token=C_Yx8W_k5t4AAAAA:gMJ0T_qAPTpZ3CW-4sRcGLrjYpu3OgWDZilMYe7arsN8VQ-fFtwqBiD5xosgdSp66ex44BbgnA)
- [43] V. Jayaraman, "Production planning for closed-loop supply chains with product recovery and reuse: An analytical approach," *International Journal of Production Research*, vol. 44, no. 5, pp. 981–998, Mar. 2006, doi: 10.1080/00207540500250507.
- [44] A. J. et al. , Afifa Jahan et al., "Mushroom Value Chain and Role of Value Addition," *International Journal of Botany and Research*, vol. 9, no. 1, pp. 5–14, 2019, doi: 10.24247/ijbrjun20192.
- [45] WBCSD, "' Value Chain ' Definitions and Characteristics," *Value Chain*, vol. 6, no. 2001, pp. 4–6, 2014.
- [46] F. O. R. Diversification, O. F. The, and R. Economy, *Market and Value Chain Specialist*, no. May. 2018.
- [47] R. Kaplinsky and M. Morris, "A handbook for value chain research," no. January 2001, 2001.
- [48] L. G. Bellù, *FAO VCA-Tool : A Software for Value Chain Analysis*. 2012.
- [49] M. E. Porter, "Technology and Competitive Advantage," *Journal of Business Strategy*, vol. 5, no. 3, p. 60, 1985, doi: 10.1108/EB039075/FULL/PDF.
- [50] "The Royal Library | kb.dk." <https://www.kb.dk/> (accessed Dec. 01, 2021).
- [51] "Statistics Denmark." <https://www.dst.dk/en> (accessed Dec. 02, 2021).
- [52] "Miljøstyrelsen | miljø, affald, støj, luft og kemi - vand, natur og friluftsliv - miljøregulering af industri, skov og landbrug." <https://mst.dk/> (accessed Dec. 02, 2021).
- [53] "Global waste generation - statistics & facts | Statista." <https://www.statista.com/topics/4983/waste-generation-worldwide/> (accessed Jul. 08, 2022).
- [54] Danish EPA, *Affaldsstatistik 2019*, no. Miljøprojekt nr. 2152. 2020. [Online]. Available: <https://www2.mst.dk/Udgiv/publikationer/2020/12/978-87-7038-249-6.pdf>
- [55] Danish Government, "Denmark without waste," no. November, pp. 1–37, 2013, doi: 978-87-03026-59-5.
- [56] StatisticsCenter, *Waste Statistics 2013*, vol. 2013, no. March. 2014.
- [57] "Statistics Denmark." <https://www.dst.dk/en> (accessed Jul. 08, 2022).
- [58] "CO2 emissions (metric tons per capita) | Data." <https://data.worldbank.org/indicator/EN.ATM.CO2E.PC> (accessed Jul. 08, 2022).
- [59] OECD, "Environment at a Glance: Circular economy, waste and materials," *Environment at a Glance*, no. May 2020, pp. 1–12, 2020, [Online]. Available: <https://www.oecd.org/environment/environment-at-a-glance/Circular-Economy-Waste-Materials-Archive-February-2020.pdf>
- [60] "Arable land (% of land area) - European Union | Data." <https://data.worldbank.org/indicator/AG.LND.ARBL.ZS?locations=EU> (accessed Jul. 08, 2022).
- [61] "Material flow accounts (env\_ac\_mfa)." [https://ec.europa.eu/eurostat/cache/metadata/en/env\\_ac\\_mfa\\_sims.htm](https://ec.europa.eu/eurostat/cache/metadata/en/env_ac_mfa_sims.htm) (accessed Jul. 08, 2022).
- [62] R. Bedoić, B. Čosić, N. D.-S. of the total environment, and undefined 2019, "Technical potential and geographic distribution of agricultural residues, co-products and by-products in the

- European Union," *Elsevier*, Accessed: Jul. 08, 2022. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0048969719322582>
- [63] E. and U. Danish Ministry of Climate, "Energy in Denmark 2020", Accessed: Jul. 08, 2022. [Online]. Available: [https://ens.dk/sites/ens.dk/files/Statistik/energy\\_in\\_denmark\\_2020.pdf](https://ens.dk/sites/ens.dk/files/Statistik/energy_in_denmark_2020.pdf)
- [64] Danish Energy Agenc, "biomasseanalyse\_final\_ren\_eng", Accessed: Jul. 08, 2022. [Online]. Available: [https://ens.dk/sites/ens.dk/files/Bioenergi/biomasseanalyse\\_final\\_ren\\_eng.pdf](https://ens.dk/sites/ens.dk/files/Bioenergi/biomasseanalyse_final_ren_eng.pdf)
- [65] K. Tomberlin, R. Venditti, Y. Y.- BioResources, and undefined 2020, "Life cycle carbon footprint analysis of pulp and paper grades in the united states using production-line-based data and integration," *ojs.cnr.ncsu.edu*, vol. 15, no. 2, pp. 3899–3914, 2020, Accessed: Jul. 08, 2022. [Online]. Available: [https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes\\_15\\_2\\_3899\\_Tomberlin\\_Life\\_Cycle\\_Carbon\\_Footprint](https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_15_2_3899_Tomberlin_Life_Cycle_Carbon_Footprint)
- [66] "Carton CO2e calculator | Tetra Pak." <https://www.tetrapak.com/sustainability/planet/environmental-impact/a-value-chain-approach/carton-co2e-footprint> (accessed Jul. 08, 2022).
- [67] A. M. Brackley, D. L. Nicholls, M. Puettmann, and E. Oneil, "United States Department of Agriculture Forest Service Pacific Northwest Research Station General Technical Report Life Cycle Assessment of Wood Energy for Residential Heating-Opportunities for Wood Pellet Production in Southeast Alaska," 2017. [Online]. Available: [http://www.ascr.usda.gov/complaint\\_](http://www.ascr.usda.gov/complaint_)
- [68] J. Sun *et al.*, "An estimation of CO2 emission via agricultural crop residue open field burning in China from 1996 to 2013," *Journal of Cleaner Production*, vol. 112, pp. 2625–2631, Jan. 2016, doi: 10.1016/J.JCLEPRO.2015.09.112.
- [69] Food and Agriculture Organization of the United Nations. and Food Wastage Footprint (Project), *Food wastage footprint : impacts on natural resources : summary report*. FAO, 2013.
- [70] K. P. Contreras, J. M. S. Yáñez, Q. Aguilar-Virgen, P. Taboada-González, and L. Marquez-Benavides, "Potential for Methane Generation by Lignocellulosic Household Waste," *Sustainability 2018, Vol. 10, Page 3461*, vol. 10, no. 10, p. 3461, Sep. 2018, doi: 10.3390/SU10103461.
- [71] E. Novaes, M. Kirst, V. Chiang, H. Winter-Sederoff, and R. Sederoff, "Lignin and Biomass: A Negative Correlation for Wood Formation and Lignin Content in Trees," *Plant Physiology*, vol. 154, no. 2, p. 555, 2010, doi: 10.1104/PP.110.161281.
- [72] S. Adhikari, H. Nam, and J. P. Chakraborty, "Conversion of solid wastes to fuels and chemicals through pyrolysis," *Waste Biorefinery: Potential and Perspectives*, pp. 239–263, Jan. 2018, doi: 10.1016/B978-0-444-63992-9.00008-2.
- [73] A. S. Rajavat *et al.*, "Sustainable use of the spent mushroom substrate of *Pleurotus florida* for production of lignocellulolytic enzymes," *Journal of Basic Microbiology*, vol. 60, no. 2, pp. 173–184, 2020, doi: 10.1002/jobm.201900382.
- [74] C. Paredes *et al.*, "Characterization of the different organic matter fractions of spent mushroom substrate," *Communications in Soil Science and Plant Analysis*, vol. 40, no. 1–6, pp. 150–161, 2009, doi: 10.1080/00103620802625575.
- [75] F. H. Mohd Hanafi *et al.*, "Environmentally sustainable applications of agro-based spent mushroom substrate (SMS): an overview," *Journal of Material Cycles and Waste Management*, vol. 20, no. 3, pp. 1383–1396, 2018, doi: 10.1007/s10163-018-0739-0.
- [76] A. Majchrowska-Safaryan, K. Pakuła, and M. Becher, "The Influence of Spent Mushroom Substrate Fertilization on the Selected Properties of Arable Soil," *Ochrona Srodowiska i Zasobow Naturalnych*, vol. 31, no. 4, pp. 28–34, 2021, doi: 10.2478/oszn-2020-0016.

- [77] E. Medina, C. Paredes, M. A. Bustamante, R. Moral, and J. Moreno-Caselles, "Relationships between soil physico-chemical, chemical and biological properties in a soil amended with spent mushroom substrate," *Geoderma*, vol. 173–174, pp. 152–161, 2012, doi: 10.1016/j.geoderma.2011.12.011.
- [78] "Supply Chain Latest: Warnings Mount Over Fertilizer Crisis - Bloomberg." [https://www.bloomberg.com/news/newsletters/2021-10-15/supply-chain-latest-warnings-mount-over-fertilizer-crisis?cmpid=BBD101521\\_TRADE&utm\\_medium=email&utm\\_source=newsletter&utm\\_term=211015&utm\\_campaign=trade](https://www.bloomberg.com/news/newsletters/2021-10-15/supply-chain-latest-warnings-mount-over-fertilizer-crisis?cmpid=BBD101521_TRADE&utm_medium=email&utm_source=newsletter&utm_term=211015&utm_campaign=trade) (accessed Jul. 08, 2022).
- [79] "Enzymes from mushrooms and their industrial applications," *books.google.com*, Accessed: Dec. 02, 2021. [Online]. Available: [https://books.google.com/books?hl=en&lr=&id=0Kzua52kfvsC&oi=fnd&pg=PA136&dq=Rahi,+D.K.,+Rahi,+S.,+Pandey,+A.K.,+Rajak,+R.C.:+Enzymes+from+mushrooms+and+their+industrial+application.+In:+Rai,+M.+\(ed.\)+Advances+in+Fungal+Biotechnology,+pp.+136%E2%80%93184.+I+K+International+Publishing+House+Pvt,+New+Delhi+\(2009\)&ots=E5QZ--uzg-&sig=OcEfo\\_bpzfbhZPKW2sG-67Aps7A](https://books.google.com/books?hl=en&lr=&id=0Kzua52kfvsC&oi=fnd&pg=PA136&dq=Rahi,+D.K.,+Rahi,+S.,+Pandey,+A.K.,+Rajak,+R.C.:+Enzymes+from+mushrooms+and+their+industrial+application.+In:+Rai,+M.+(ed.)+Advances+in+Fungal+Biotechnology,+pp.+136%E2%80%93184.+I+K+International+Publishing+House+Pvt,+New+Delhi+(2009)&ots=E5QZ--uzg-&sig=OcEfo_bpzfbhZPKW2sG-67Aps7A)
- [80] A. Grimm, L. Eilertsen, F. Chen, R. Huang, L. Atterhem, and S. Xiong, "Cultivation of *Pleurotus ostreatus* Mushroom on Substrates Made of Cellulose Fibre Rejects: Product Quality and Spent Substrate Fuel Properties," *Waste and Biomass Valorization*, vol. 12, no. 8, pp. 4331–4340, 2021, doi: 10.1007/s12649-020-01311-y.