MUSHNOMICS

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

D1.1 - Mushroom Value Chain Analysis

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The MUSHNOMICS Consortium partners are the following:

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Table of contents

List of Figures

List of Tables

Acronyms

Acronym	Full Text
EU	European Union
TP-A	Time Period A
TP-B	Time Period B
MSW	Municipal Solid Waste
VCA	Value Chain Analysis
SMS	Spent Mushroom Substrate

1 Executive summary

In the EU, over 1 million tonnes of mushrooms were produced in 2020 (Eurostat). Beyond production, there are important aspects that a value chain analysis (VCA) can elaborate on such as waste generation, circularity of economic activities, distribution of value between actors of the value chain, relationships between and within realms of productive activities, and social dynamics. Hence, the aim of this deliverable was to provide insights and descriptions of different value chain agents including their activities, current practices, and challenges and opportunities for improvement in the mushroom value chain by conducting a VCA in the four consortium countries: Denmark, Ireland, Hungary, and Romania with a particular focus and detailed investigation in Denmark and Ireland, based on data availability. The VCA showed that Denmark was the only country with a negative trade balance, as it consumed around 6,200 tonnes of mushrooms more than it produced per year on average from 1991-2017. We also found that Ireland neither imported nor exported substrate, indicating a complete domestic reliance on substrate production. We also identified economic distributions of value, such as import and export prices, while also noting the cost of production and consumption where data was available. After mapping physical flows and economic activities, we focused our VCA in Ireland and Denmark by undertaking a thorough accounting of mushroom production and consumption activities; this included listing actors into a potential stakeholder group, mapping the area of activities, and conducting surveys to determine market trends and hear real experiences of the actors to better understand the enabling environment and the extension services that exist in the mushroom value chain. For instance, for Ireland, we found that over 80% of mushrooms are made to be exported to the UK, with corresponding organization around this impetus. We have also identified that Denmark has a structural market composition of one large producer for primary grocery store product delivery, and many other divergent actors filling the supply for a growing demand of niche exotic mushrooms like oyster, shitake, and lion's mane. However, with very few local producers of substrate or fungal genetic material such as spawn or liquid culture, Denmark is vulnerable to supply chain interruptions or tensions, such as those generated by the Coronavirus. Therefore, this VCA has identified points of mushroom value chain weaknesses and strengths in four different countries, which will pave the way for increasing production while highlighting new directions for consumption and production methodologies.

2 Introduction

Mushrooms are the common name for the fruiting bodies of different types of fungi; in this deliverable we will focus on those used for human consumption. There are two main types of cultivated mushrooms: primary decomposers, such as oyster or shiitake mushrooms, and secondary decomposers, such as button mushrooms. They are found worldwide, and are functionally diverse, with many contributing to human dietary and health needs. Because of the nutritional value, vitamin content, as well as the growing need for diverse vegetarian foods and high protein content meat alternatives, worldwide 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 [1]. The production of mushrooms worldwide was estimated to be worth approximately 42 to 63 billion USD during 2013 [1], [2], with this activity generating 170-204 million tonnes of spent mushroom substrate (SMS) in 2013 [1], [3]. Accounting by genus, 22% of global production in 2013 was for *Lentinula* (shiitake), 19% was for *Pleurotus* (oyster), 18% for *Auricularia* (wood-ear), and 15% was for *Agaricus* (button) [1]. Furthermore, these production values are only increasing over time, although contemporary accurate data on Chinese production, which is the majority of the world's production, is lacking.

As a result of the relatively inexpensive costs for acquiring suitable raw materials, such as those from agriculture, household, or industrial waste, mushroom farming is increasing in popularity and scope in urban and peri-urban environments [4], [5]. These suitable raw materials derived from waste include certain types of food waste or animal manure which are composted and used for secondary decomposers such as *Agaricus bisporus* (button); furthermore, coffee grounds, garden waste, agricultural by-products such as wheat straw, rice husk, corncobs, and cotton waste, as well as paper and cardboard, discarded textiles, and woody products such as sawdust can be used for primary decomposers such as *Pleurotus ostreatus* (oyster), or *Lentinula edodes* (shiitake) [6]–[13]. The wide and varied potential of mushrooms to grow on a variety of human-produced waste sources lends them as effective allies for the achievement of a circular economy that minimizes waste in its own production by utilizing waste from other sectors of economic activity, while also producing high quality goods that are valuable for human health and well-being.

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 tons (Figure 1) [14]. Figure 1 demonstrates that after an increase from 2018 to 2019, mushroom production fell by 4% from 2019 to 2020, likely due to the Coronavirus epidemic. 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 (Table 1). 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 (Table 1). 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, ruminant feed, compost input, soil amendment, agricultural fertilizer pellets, or anaerobically digesting it for the production of biogas [15]. 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 [16]–[18]. Therefore, the costs of processing this waste stream in Europe would cost 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. Although SMS as a waste stream has many potential uses, it is still not being used to its fullest. Therefore, emphasizing more circular use of SMS would reduce costs associated with disposing it, as well as potentially creating value downstream through valorization schemes such as vermicomposting or biogas generation.

Figure 1. Production of mushrooms in the EU and United Kingdom from 2012 to 2020. Colors correspond to specific countries, or groups of countries, as listed in the legend.

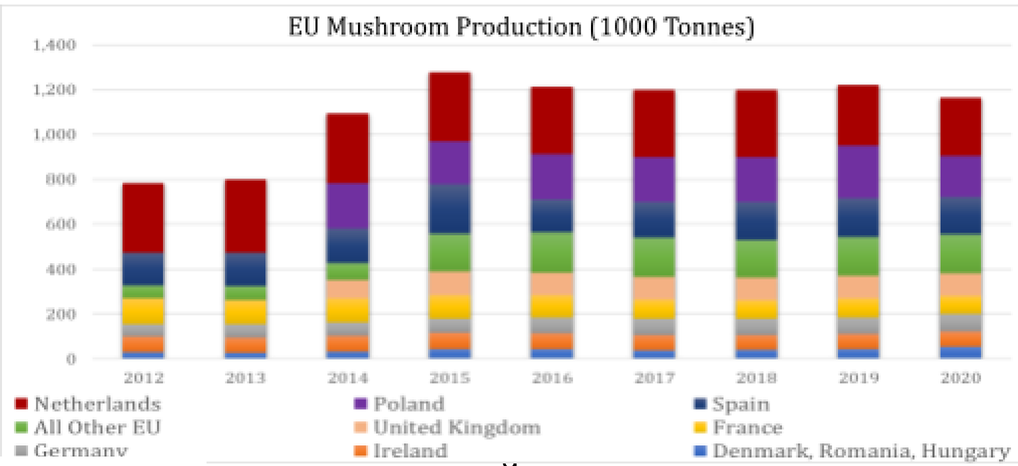


Table 1. *Tabulated mushroom and SMS production for consortium countries during 2016 and 2020.*

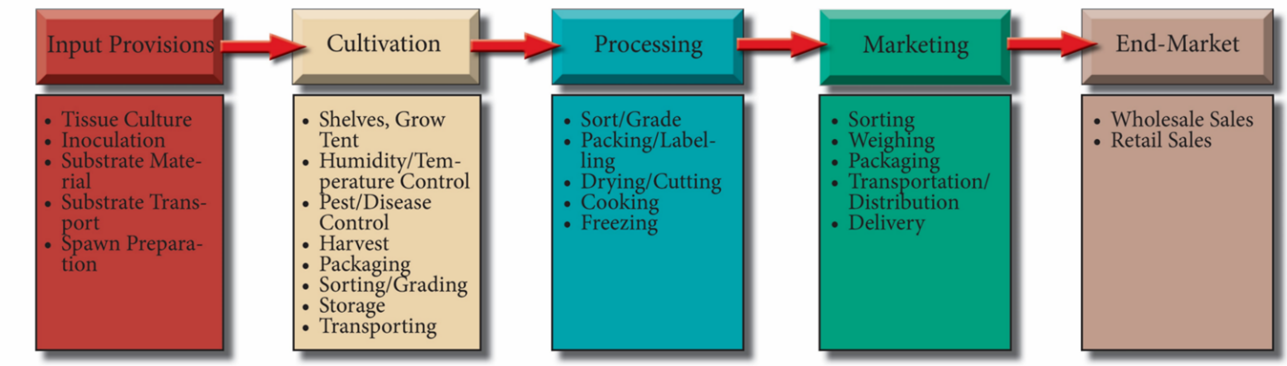
	Mushroom (2016)	Mushroom (2020)	SMS (2016)	SMS (2020)
Denmark (tonnes)	3,930	4,682	9,607	11,444
Hungary (tonnes)	24,650	39,400	60,256	96,311
Ireland (tonnes)	70,020	69,260	171,160	169,302
Romania (tonnes)	14,520	14,320	35,493	35,004
consortium Total (tonnes)	113,120	127,662	276,516	312,062
EU Total (tonnes)	1,213,000	1,063,000	2,965,111	2,598,444
consortium country prod. (%)	9.3%	12.0%	9.3%	12.0%

2.2 Aim and objectives of study

The aim of this deliverable is to understand the mushroom value chain dynamics using recent literature, databases, surveys, interviews and field visits. Therefore, the components of the supply chain were studied (e.g., the key players within the supply chain, the geographical location of constituents, logistical issues, the volume, and variety of materials moving through the supply chain), while also noting the relevance of inter-supply chain relationships (e.g., the interactions between different supply chains), and discussing the regulatory and institutional issues affecting each constituent of the supply chain. The literature review, databases, surveys, interviews and field visits provided insights and descriptions of different value chain agents including their activities, current practices, challenges and opportunities for improvement in the mushroom value chain. We accomplished this using the methodological lens of a value chain analysis (VCA), which is essentially a supply chain analysis with additional focus on internal and external agents that acquire or provide value to a production process.

In this regard, Figure 2 demonstrates value chain activities under five main overarching categories, with the corresponding actions beneath that are carried out by each value chain agent in the mushroom value chain. Each of the categories includes both methodological activities and consumables. This organizational structure and example activities are derived from the literature on VCA and have been applied to the mushroom production context [19]–[29]. The different agents are production input providers, producers, processors, and point-of-sale markets, which operate within or between different structural entities (companies). That is, some companies specialize in a few areas, while others span the continuum of activities. The production input providers supply substrate, culture, or spawn-run grow bags, which are bought by the cultivators to produce the mushroom for sale and consumption. The processors add value to the fresh mushroom by packaging, drying, or engaging in other means to enhance the shelf life or sell at a higher price compared to the fresh produce. The market section includes transportation and outlets such as supermarkets, restaurants, online webshops, or farmer's markets, where mushrooms in different packaging and forms are sold directly to the consumers. Based on the availability of data, our study had a particular focus on mapping the mushroom value chain in Denmark and Ireland, with comparisons of production statistics to other consortium countries, and documentation of activities carried out by different value chain agents as revealed from research, surveys, interviews, and field visits.

Figure 2. Mushroom Value Chain Analysis mixed format schematic.



Conducting our VCA was used to contextualize existing advantages and disadvantages of the mushroom supply chain given changing regulations, perceptions, or other influential factors such as global pandemics (e.g. the Coronavirus), which impacts the activities and access to activities that supply chain actors experience. This deliverable describes the mushroom production context in consortium countries in Section 4. Based on the availability of data, the VCA undertaken here focused on the mushroom production dynamics in Denmark, Ireland, Romania, and Hungary. Section 5 discusses the responses gathered through questionnaire surveys, field visits, and interviews with stakeholders across the mushroom value chain. This was done in Denmark and Ireland based on data availability.

3 Methodology

Conducting a VCA generally consists of four key steps. Firstly, systematically mapping actors across the value chain from production, distribution, markets, to disposal. This map is traditionally made up of these central productive efforts, but it is also important to contextualize their activities via the enabling environment such as infrastructure and institutions, and extension services that support operations, such as consultants or logistical expertise [21]–[25], [28]. 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, examining the role of upgrading or improving the production process via quality or design features; this is focused on more thoroughly in *Deliverable 1.3: Gap Analysis.* Fourthly, highlighting the function of governance structures or current events on production activities to help explain their operations and distribution of benefits.

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 data and Google Scholar for the majority of our literature review [30]. 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 [31], which is a publicly accessible repository of a wide variety of statistics that are gathered for the entirety of Denmark. Financial data were obtained from the publicly-accessible website on all registered companies in Denmark, virk.dk [32]. Additional Danish information was obtained from the Ministry of Environment publications [33].

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. Our survey template is attached in the appendix of this document (Figure 1A). The key questions concerned four activities: mushroom production, substrate, current challenges and solutions, and supply chain issues. We organized our VCA approach by tracking the value chain agents, activities and material flows along the mushroom value chain, from inputs to market. Based on our materials, we identified and classified the different inputs, activities, outputs, actors, and challenges associated with each of the different steps in the mushroom production chain. The process of undertaking our VCA also defined the different actors for our stakeholder network.

4 Mushroom Value Chain Analysis

4.1 Mushroom production and consumption trends

There are two general types of mushrooms produced commercially for human consumption: the first is wood-decomposing species of 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 [34]–[39]. These are known as 'primary decomposers' which selectively degrade lignin and hemicellulose, often leaving cellulose which can be used by ruminants, or other fungi, downstream [40], [41]. One of the most popularly cultivated types of mushrooms grown worldwide is *Pleurotus spp.*, with one of the reasons being their robustness and relatively simple cultivation practices, such as growing effectively on chopped, sanitized, and water-soaked straw [42], [43]. In general, they have a very wide potential feedstock from coffee grounds, sawdust, straw, logs, other crop residues such as stalks, leaves, or husks, and many other sources [12], [41], [43]–[45]. The second type of commonly cultivated fungus is saprotrophic secondary decomposing basidiomycetes, also known as litter decaying fungi, such as *Agaricus bisporus*, or button mushroom, which requires compost as well as a layer of casing for production [46]–[49]. The casing layer should have a high-water holding capacity, good air pore ratio, and low bulk density [50]. The most common casing layers are composed of peat moss, loam soil, Spent Mushroom Substrate (SMS), or various types of livestock slurries [6]. However, it should be noted that the widespread reliance on peat moss has potential environmental consequences, and continued over-use is unsustainable [51]. This input will therefore require replacement sometime in the future. Beyond these basic methodological differences, both of these mushroom types can benefit from supplementation: in the case of wood-decaying mushrooms, this can come from nitrogenous material such as oat bran or urea; for litter decaying mushrooms, this can come from cotton cake, wheat bran, lentil powder, or even SMS [4], [7], [52]–[56].

In Denmark, as in most other European countries, the majority of mushrooms produced are button mushrooms, with increasing production rates of oyster mushrooms and other white rot fungi such as shiitake and lion's mane on the rise. Overall, the Danish mushroom production dynamics, as derived from the existing statistical information (seen in Table 2 and Figures 3 and 4), can be categorically separated into two time periods from 1991-2009, which we refer to as Time Period A (TP-A), and from 2010-2017, which we refer to as Time Period B (TP-B). The TP-B stops in 2017 because mushroom production in Denmark slowed enough that Statbank stopped collecting production data. Our representative division of time periods is the result of the events of 2010, which saw a 68.5% reduction in domestic Danish production in a single year. This reduction is likely the result of the great financial crisis in 2008, which depressed demand, affected supply chains, and caused company closures. In this regard, Table 2 shows that the initial time period, TP-A, saw much cheaper manufacturer's input materials costs per tonne of mushroom produced with an average of 9 Euros/tonne. TP-A also had an associated average annual mushroom production of 9,380 tonnes/year domestically. However, for TP-B, the average manufacturer's input material costs per tonne of mushroom produced was 114 Euros/tonne, with only 3,252 tonnes/year domestic mushroom production on average.

It is also worth noting that from 2012 to 2017, the share of organic mushroom production increased from 2% up to 21% of total production; if we estimate 4,000 tonnes of domestic production for 2018-2020, the organic production share increased up to 41% of total production from 2012 to 2020. Furthermore, the average total GDP at factor cost/tonne of mushroom produced was 1,487 Euros/tonne during TP-A, and 2,735 Euros/tonne during TP-B. The metric GDP at factor cost includes the inputs of labor costs, land or infrastructure costs, interest or financial costs, or private profit generation. This near-doubling increase of GDP at factor cost from TP-A to TP-B could help explain why Danish mushroom production slowed after 2010: as supply chains disconnect, supply inputs must be re-sourced, which can increase input costs, or even force companies to go bankrupt (see section 5.6 for an example). The increase in GDP at factor cost in TP-B also shows that there is a lot more economic activity associated with mushroom production in TP-B compared to TP-A; however, using this metric makes it is hard to say where the majority of the increase came from via different inputs. Despite this, with the values for manufacturer's input materials costs increasing so much as well, it is likely that GDP at factor cost increased in large part due to inputs.

Table 2. Comparison of TP-A (1991-2010) and TP-B (2011-2017) for different mushroom related factors in Denmark. Mush. = mushrooms; Prod. = production; Num. of Prod. = number of producers.

	Input cost	GDP at Factor Cost	Mush. Prod.	Mush. Cons.	Mush. Import	Mush. import price	Mush. Export	Mush. export price	Import/ Export Ratio	Num. of Prod.	Grow Bed Area
Unit	**Euro /ton ne**	**Euro /tonne**	**tonne s**	**tonnes**	**tonnes**	**Euro /tonne s**	**tonnes**	**Euro /tonne**	**Ratio**	**#**	**m^2**
TP-A Avg. (1991-2009)	9	1,487	9,380	14,169	8,410	1,585	3,059	1,367	2.8	16	70,542
TP-B Avg. (2010-2017)	114	2,735	3,252	13,936	11,576	1,939	892	2,125	13.0	13	29,443

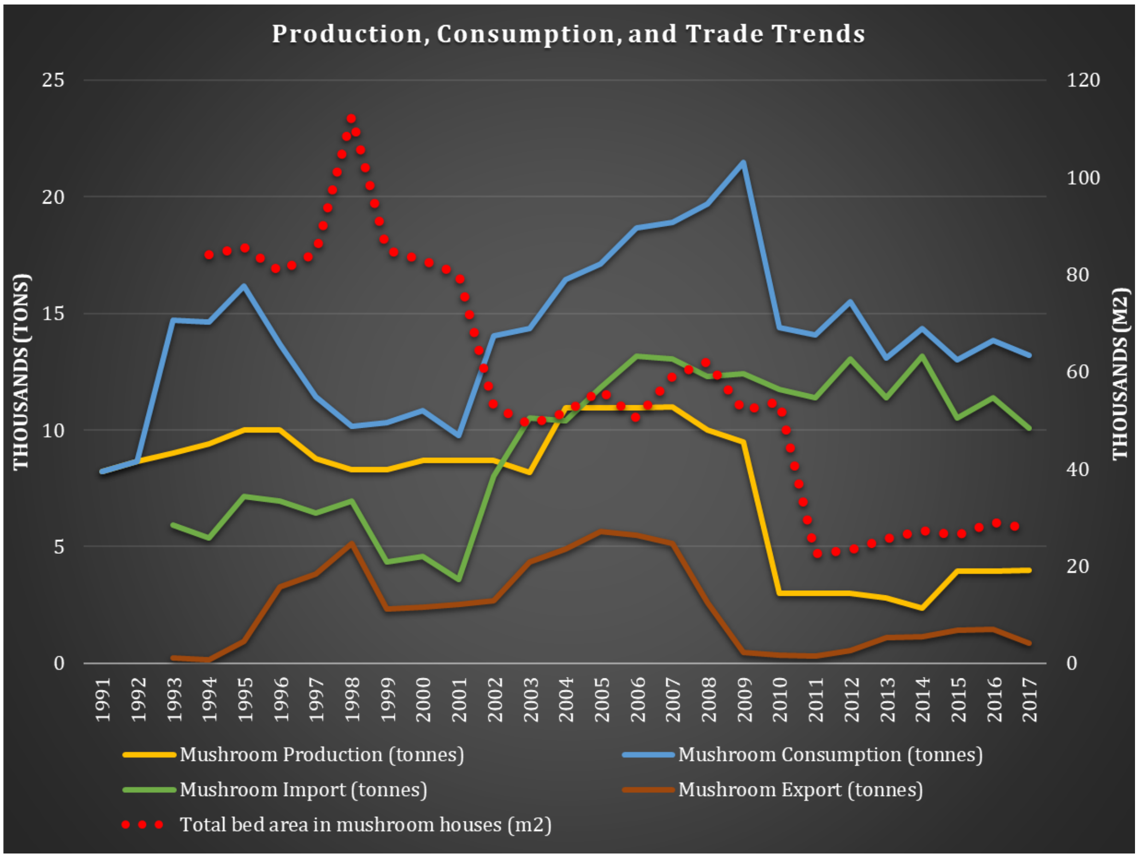
**All data were sourced from Statbank, except for Mushroom Production (tons), which is derived from the FAO*

The data in Table 2 demonstrate that during TP-A 8,410 tonnes/year of mushrooms were imported, while during TP-B 11,576 tonnes/year on average were imported. Furthermore, during TP-A, the import price was 1,585 Euros/tonne; during TP-B, the import price was 1,939 Euros/tonne. Therefore, TP-B imported 27% more mushrooms at a 17% higher price/tonne compared to TP-A. Beyond imports, TP-A exported 3,059 tonnes/year of mushrooms, with TP-B exporting only 892 tonnes/year on average. Furthermore, for TP-A, the export price was 1,367 Euros/tonne; for TP-B, the export price was 2,125 Euros/tonne. Although TP-B had a higher export price, this dynamic was not realized to its potential, as the average amount of exports decreased by 71%. This decrease closely mirrors the mushroom production decrease from TP-A to TP-B, which was 65.3%, for reasons discussed above. Furthermore, another way to demonstrate the differences between material flows of mushrooms through Denmark is an import/export ratio, which had a value of 2.8 in TP-A, and 13.0 in TP-B, meaning there were 2.8 times more mushroom imports in TP-A, and 13 times more mushroom imports in TP-B, than there were exports. There is also historical and contemporary data on mushroom consumption, which in Denmark was 8,217 tonnes/year in 1991 and increased up to 15,256 tonnes/year in 2020. One way to identify points of value-creation interventions is to conceptualize this via a production-consumption gap, which had an average value of 4,789 tonnes in TP-A, and 10,683 tonnes in TP-B (i.e., consumption greater than domestic production). This means that 6,000 additional tonnes of mushrooms were consumed in Denmark on average per year than were domestically produced in TP-B compared to TP-A.

There is also information on producer dynamics in Denmark. For instance, there was an average of 16 mushroom producers (of various sizes and market percentages) per year in TP-A, with an average of 12 producers in TP-B. Excluding 2017, the average for TP-B is 9, as there were 40 total producers in 2017. This is a near halving of the average number of producers from TP-A to TP-B, with the initial value of 31 producers in 1994 decreasing down to 6 in 2009, where it has been rising since (Figure 4). For instance, 2017 shows that this dearth of producers is rebounding as many more small-scale producers are taking up residence. Furthermore, the average grow bed area per producer in 2010 was 6,733 m^2, which decreased almost ten-fold down to 690 m^2 per producer in 2017. This could be in small part because of Denmark's small-business-friendly laws, which have low business registration fees, free municipality courses on starting a business, and clear paperwork guidelines. In the survey section, we will also discuss how public perceptions about a 'green revolution' in Denmark, including small-scale production, are leading to more localized business activity generation. However, more small-scale activity at its current levels is not meeting Danish consumption demands, as indicated by the total mushroom grow-bed area in use in Denmark, which was 70,542 m^2 on average in TP-A and was 29,443 m^2 on average in TP-B. Relatedly, the grow-bed area in 2010 was 53,869 m^2, which decreased to 22,531 m^2 in 2011. There was also a 17% decrease in total mushroom bed area from 27,608 m^2 in 2017 down to 22,589 m^2 in 2018. This is likely the result of the closure of Egehøj Champignon, which was one of Denmark's largest producers. See section 5.6 for more details. Beyond mushroom production, there are also input flows to consider, such as spawn dynamics. For instance, in TP-A, an average of 211 tonnes/year of spawn was imported, and 61 tons/year was imported in TP-B. This 71% decrease in spawn importation closely mirrors the production decline as well. The average price/tonne of spawn imported in TP-A was 2,778 Euros/tonne, and was 2,415 Euros/tonne in TP-B. For exporting spawn, 22 tonnes were exported per year in TP-A, and 0.5 tonnes/year in TP-B.

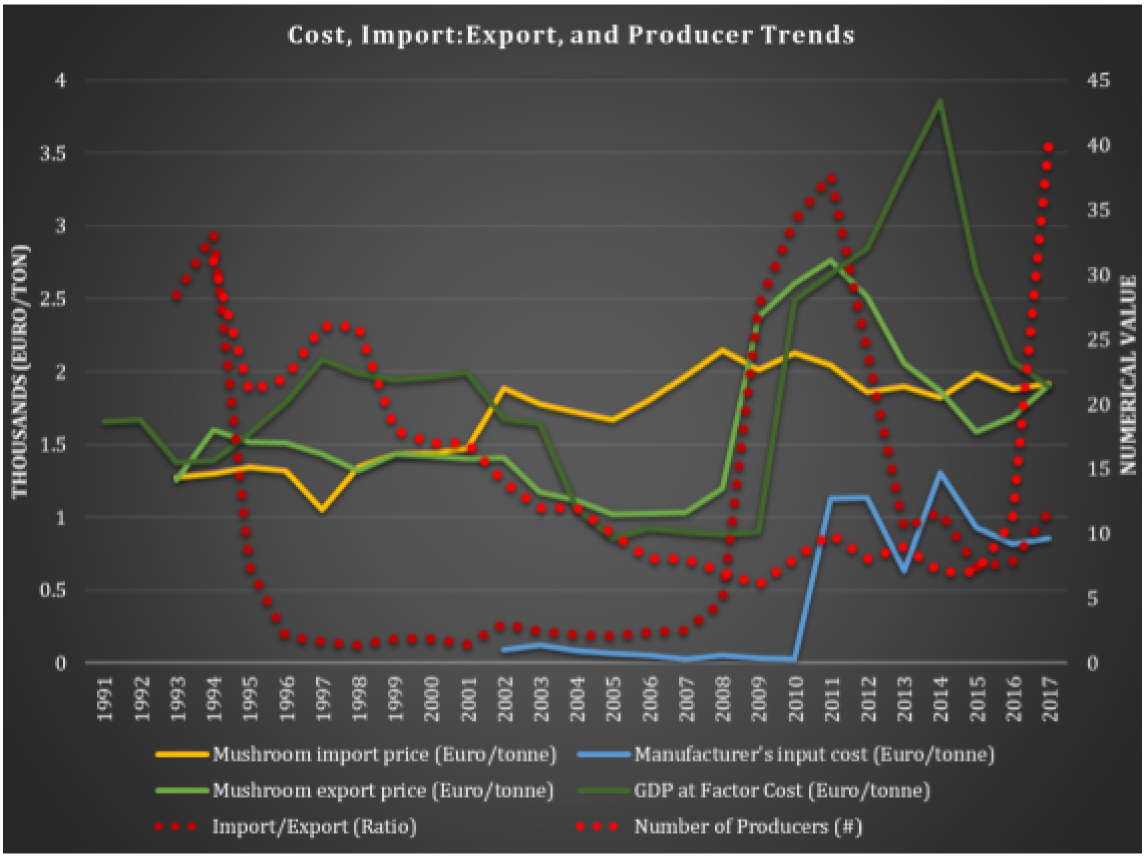
Although there are interesting differences between the two categorical time periods (TP-A and TP-B), we can also look at the macro trend for all the available data seen via the production, consumption, and trade trends in Figure 3. The dotted red line shows the total mushroom bed production area which is associated with the secondary axis (thousands of m^2) on the right. The rest of the trend lines follow the primary axis (thousands of tons) on the left. The trend data for Figure 3 show a pattern whereby mushroom production activities increased until about 2007; this includes exports, which had increased overall from 1993 to 2007, where Denmark was exporting around 5,000 tonnes a year. However, the first decrease was seen in the volume of mushroom exports; the production, consumption, import, and grow bed area values soon decreased as well in 2009-2010. Unsurprisingly, the actual material footprint of grow bed area was the slowest to react to depressed demand and existing trends. The import values were the least affected, even as consumption dropped significantly. A collapse in domestic production explains this, which was compensated for by imports.

Figure 3. Production, Consumption, and Trade Trends from 1991 to 2017 in Denmark. The dotted red line follows the secondary axis on the right. Units for the primary axis are thousands of tons; secondary axis units are thousands of m^2.



Another series of mushroom activity values can be seen in Figure 4, which shows cost, import:export ratio, and producer trend data. The dotted red lines show the import:export ratio and the number of producers which are associated with the secondary axis (numerical value) on the right, while the non-red lines are associated with the primary axis (thousands of Euros/tonne) on the left. Some interesting results show that the import price stayed relatively stable over time, although it did increase overall. Unsurprisingly, the export price was mirrored by the increase in GDP at factor cost around the financial crisis (2008-2010). This is reflected by the similar increase in manufacturer's input costs from 2010-2011, which is likely due to supply chain interruptions that were compensated by for local sources with higher input costs. Interestingly, the GDP at factor cost increased past the export price, but ended up converging in line with both the export and the import price in 2017. This could be the result of supply chain issues associated with the financial crisis of 2007-2008, which we are seeing similarly reflected in many parts of the economy now due to the Coronavirus. It is likely that the GDP at factor cost, including manufacturer's input costs, increased so much due to input crises such as shortages of critical supplies such as substrate. This input cost, if supplies are disrupted, can potentially be so high that large companies will go bankrupt if they cannot produce their own. An example of this occurring in Denmark is discussed in Section 5.6.

Figure 4. Cost, Import:Export, and Producer Trends from 1991 to 2017 in Denmark. Dotted red lines follow the secondary axis on the right. Primary units are thousands of Euros/tonne; secondary units are import:export ratio and number of producers, both as numerical values.



4.2 Comparable VCA aspects in consortium countries

Table 3 expands on the Danish VCA aspects by showing averaged macro trend data for imports, exports, difference/local demand gap, local production, local consumption, and demand gaps for the four consortium countries: Denmark, Romania, Ireland, and Hungary. 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. In opposition to this, 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 tons/year on average for 2010-2019. This was sold on the market for approximately 74,298,506 Euros/year. 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. Romania also had a positive trade balance, with 4,493 tonnes/year more mushrooms being exported than were imported on average from 2013-2020. The above 'cost' values are derived from the export or import price per tonne: for instance, in Denmark, the average mushroom import and export prices over the entire data time period (1996-2020) were nearly identical: 1,800 Euros/tonne and 1,748 Euros/tonne, respectively. For Ireland, their import value was 1,945 Euros/tonne from 2010-2020, and was 3,474 Euros/tonne for exports. This demonstrates that Ireland, which is a much larger mushroom producer than Denmark, has a much better export price as well. For Romania, the import and export value were both 1,250 Euros/tonne on average from 2013-2020, which is also significantly lower than Denmark.

Another key aspect of contextualizing mushroom production in the four consortium countries looks at production data. 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. 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. 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. 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. Unsurprisingly, with Denmark being the most expensive of the four countries to live in, it had the highest input costs per tonne of mushrooms produced; Ireland was second, with Hungary and Romania having around the same cost in third. The degree of input cost differences due to comparative advantage (which describes a country's ability to produce a good/service at a lower opportunity cost than others) or consumer purchasing power (cost of living indices) can only be estimated. For instance, because the mushroom production market is not transparent, there could likely be comparative advantages in specific countries that explain more cost variation than cost of living indices.

Table 3. Comparison of available data on import, export, production, consumption, and corresponding supply/demand gaps in Denmark, Romania, Ireland, and 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
DENMARK	*Data Range*	*(Average for 1996-2020)*	*(Average for 1996-2020)*	*(Average for 1996-2020)*	*(Average for 1991-2017)*	*(Average for 1996-2020)*	*(Average for 1996-2020)*
	Substrate spawn (tonnes/year)	139	14	-124	ND	33,618	ND
	Monetary value (Euros/year)	228,420	46,435	-181,985	ND	55,832,388	ND
	Mushroom (tonnes/year)	10,053	2,359	-7,694	7,564	13,790	-6,226
	Monetary value (Euros/year)	18,097,362	4,124,611	-13,972,750	14,604,227	149,469,810	
	Price per tonne (Euros/tonne)	1,800	1,748		1,931	10,839	
ROMANIA	*Data Range*	*(Average for 2013-2020)*	*(Average for 2013-2020)*	*(Average for 2013-2020)*	*(Average for 2012-2020)*	*(Average for 2013-2020)*	*(Average for 2013-2020)*
	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	
IRELAND	*Data Range*	ND	ND	ND	*(Average for 2005-2019)*	*(Average for 2005-2019)*	*(Average for 2005-2019)*
	Substrate (tonnes/year)	0	0	0	201,163	201,163	0
	Data Range	*(Average for 2010-2019)*	*(Average for 2010-2019)*	*(Average for 2010-2019)*	*(Average for 1991-2019)*	*(Average for 1991-2019)*	*(Average for 1991-2019)*
	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	
Hungary	*Data Range*	*(Average for 2010-2020)*	*(Average for 2010-2020)*	*(Average for 2010-2020)*	*(Average for 2010-2020)*	*(Average for 2010-2020)*	
	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	

One way to compare the meaning of the different costs of production is to look at consumption prices and discussing the differences between the value generated along the value chain as shown in this table. For instance, in Denmark, it costs 1,931 Euros/tonne of mushroom produced; in Ireland, this cost is 1,755 Euros/tonne. However, the store price in Denmark (the consumption price index) means that a tonne of mushrooms sells for, on average, 10,839 Euros; in Ireland, this is 8,900 Euros. One explanation for this price difference can be the purchasing power differences between the countries. Ireland overall has a 10% lower consumer purchasing power compared to Denmark [57]; furthermore, a survey of market items showed an average lower cost of 24.86% of staple items such as a loaf of bread, rice, vegetables, fruit, meat, and milk [57]. In relation to this, the average price of mushrooms sold per tonne is 18% lower in Ireland compared to Denmark. This lower price could also be the result of Ireland's comparative advantage when it comes to mushrooms, as they produce around 8 times more mushrooms per year than Denmark (this number is much higher today than the averaged historical data shows, at around 15 times more mushrooms produced last year in Ireland than Denmark, assuming 4,000 tonnes of Danish production). Another useful comparison is Hungary and Denmark; the former had a consumption price (market price) of only 2,060 Euros/tonne of mushrooms purchased. This means Danish mushrooms are 426% more expensive to purchase from markets than in Hungary. Standard consumer purchasing power differences state that consumer prices in Denmark are 153% higher than in Romania [58]. Therefore, the rest of the price difference could perhaps be explained by comparative advantage, including differences in union membership or labor costs; for instance, <10% of the Hungarian workforce is unionized, with around 66% of Denmark being unionized [59]. These comparisons demonstrate that there are external factors influencing the price of mushroom production and consumption; these differences can in part be explained by consumer purchasing power or comparative advantage, but other aspects feed into these metrics as well. In this regard, we discuss in detail some of the explanatory context in Denmark as revealed by surveys, field visits, and interviews in Section 5.

Finally, it is worth noting the local demand gap in each of the countries, which tabulates the difference between the production of each country and its 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. Ireland, Hungary, and Romania all had a positive demand gap, as they produced more than they consumed: Ireland had a value of 20,741 tonnes (59,690-38,949 tonnes); Hungary had a value of 13,155 tonnes/year (21,997-8,842 tonnes); and Romania had a value of 5,423 tonnes/year (12,466-7,043 tonnes). Of the four partner countries, only Denmark had a negative demand gap, which is surprising 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% down in 2017 where Denmark exported less than 1,000 tonnes. This is a value chain intervention that will be addressed in *Deliverable 1.3: Gap Analysis*.

Beyond mushrooms, there is also data on inputs such as substrate and spawn imports and exports. For instance, on average, Denmark imported 139 tonnes of spawn, and exported only 14 tons of spawn per year from 1996-2020. The local demand gap for these inputs illustrates the difference between what was imported and what was exported; this trade imbalance shows that, for Denmark, 124 tonnes more spawn was imported than exported, with a cost of 181,985 Euros. As there are no industrial suppliers of substrate in Denmark, the local production for sale is 0, although 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 on average from 1996-2020, with a cost of 55,832,388 Euros. This cost is derived from market research and real prices paid which is discussed and shown in Section 5.2. On a related note, Ireland neither exported nor imported any substrate; it produced all that it needed domestically: from 2005-2019 this value was around 201,163 tons of substrate produced. Denmark could therefore benefit by imitating this and producing their own substrate domestically.

5 Mapping of Value Chain Agents

5.1 Stakeholder mapping and SWOT analysis in Ireland

The mushroom industry is the largest horticultural sector in Ireland and has a farm gate value of €119 million, which is mainly attributed to button mushrooms (*Agaricus bisporus*) according to Teagasc (2020). Production in Ireland is steady at around 68,000 tons per year, 85% of which is exported to the UK, the rest is supplied to the Irish market. There are approximately 34 growers producing on 40 farms in Ireland. Some of these growers can be seen listed in Table 4. The industry overall employs 3,500 people. The number of growers and production units has declined over the past decade as small farms ceased production, while larger farms continued to expand to ensure they remained sustainable. The Irish industry is based on a satellite grower system, whereby growers are linked into a small number of mushroom substrate producers and marketing companies. Compost production and cultivation of *Agaricus bisporus* are largely integrated in Ireland with a few companies dominating both areas. The Monaghan Mushrooms Group is the European market leader in mushroom production and marketing. They supply a full range of top-quality fresh mushrooms to leading national and international retailers in the UK, Ireland, Canada and USA. There is only a small quantity of specialty mushrooms grown in Ireland, the most common being shiitake and oyster (including only three producers of oyster mushrooms) due to low demand and cheaper costs of production elsewhere in Europe. Cost of production in Ireland is also affected by having to import spawn from the Netherlands for these species.

In Ireland there are currently three producers of substrate for *Agaricus bisporus* domestically, two located in the Republic of Ireland and one located in Northern Ireland. The three main substrate producers are Walsh Mushrooms located in Co. Wexford in the Southeast, Monaghan Mushrooms located in Co. Kildare in the Midlands and Northway Mushrooms located in Co. Armagh in the North (Table 4). The materials used are bales of straw, poultry manure, horse manure, water, and gypsum. All the materials are locally sourced, with manure and straw coming from local farmers in the area and gypsum sourced from Kingscourt, County (Co.) Cavan in the North. Another important substrate material that is highly relevant for secondary decomposers such as *Agaricus bisporus*, is peat, which is a vital component of mushroom production In Ireland. Peat is used as a casing layer and is essential for the formation of mushrooms. Currently in Ireland there is a shortage of peat following a September 2019 High Court ruling, which stated that harvesting of peat from Irish bogs greater than 30ha "now requires navigating a complex licensing and planning regime – which has resulted in horticultural peat harvesting all but ceasing" according to Growing Media Ireland (GMI).

Table 4. Overview of mushroom production value chain agents identified in Ireland

Company Name	City	County	Activity
Annaghmore Mushrooms	Annaghmore	Co. Armagh	Agaricus bisporus
Ballyhoura Mountain Mushrooms	Ballyhoura	Co. Limerick	Wild mushrooms and products
Ballyleague Mushrooms	Lanesboro	Co. Roscommon	Agaricus bisporus
Bridge Mushrooms	Mayobridge	Co. Down	Agaricus bisporus
Breffni Mushrooms	Kill	Co. Cavan	Agaricus bisporus
Codd Mushrooms	Tullow	Co. Carlow	Agaricus bisporus
Drumbo Mushrooms	Drumbo	Co. Monaghan	Agaricus bisporus
FancyFungi	Killinick	Co. Wexford	Oyster, shiitake, exotics, wild
Garryhinch Mushrooms	Garryhinch	Co. Offaly	Exotic mushrooms
Goldcircle Mushrooms Ltd	Monaghan	Co. Monaghan	Agaricus bisporus
J McCann Ltd (Ard Mhacha Mushrooms)	Silverbridge	Co. Armagh	Oyster, shiitake, exotics
Keenaghan Mushrooms	Dungannon	Co. Armagh	Agaricus bisporus
McKenna Mushrooms Limited	Tara	Co. Meath	Agaricus bisporus
Monaghan Mushrooms Ireland	Tyholland	Co. Monaghan	Agaricus bisporus
Monaghan Mushrooms Claremorris	Claremorris	Co. Mayo	Agaricus bisporus
Monaghan Mushrooms Pleroma	Dungannon	Co. Tyrone	Agaricus bisporus
Reilly Mushrooms	Athlone	Co. Westmeath	Agaricus bisporus
Walsh Mushrooms	Clougheleigh	Co. Tipperary	Agaricus bisporus
Custom Compost UC (Walsh Mushrooms)	Gorey	Co. Wexford	Substrate (Agaricus bisporus)
MONAGHAN MUSHROOMS (CARBURY SUBSTRATE FARM)	Carbury	Co. Kildare	Substrate (Agaricus bisporus)
NORTHWAY MUSHROOMS	Ballygawley	Co. Tyrone	Substrate (Agaricus bisporus)
HARTE PEAT LTD	Clones	Co. Monaghan	Peat casing
MCDON SUBSTRATES	Coalisland	Co. Tyrone	Peat casing
JF MCKENNA LTD	Armagh	Co. Armagh	Shelving, tunnels and houses
Luman-shelves	Dernaroy	Co. Monaghan	Mushroom shelving, trays
Axis technology & Development	Craigavon	Co. Armagh	Mushroom harvesting systems
SYLVAN IRELAND	Navan	Co. Meath	Fungal technology, spawn
Commercial mushroom growers	Newgrove industrial estate	Co. Monaghan	Organisation, 50% of production
Northway Mushrooms	Blackwatertown	Co. Arnagh	Organisation of 27 producers
Growing media Ireland	Athlone	Co. Westmeath	Horticultural peat suppliers
Mushroom advisor, teagasc	Dundalk	Co. Luth	Advisory, extension services

Part of the Market research and value chain analysis requires an identification of stakeholders in the value chain in Ireland such as Commercial Mushroom Growers, Substrate & Casing Producers, Equipment Manufacturers, Waste Management Companies, City Council Park Waste sites, Packaging and Distribution Facilities. These have been mapped out in Figure 5 below, where data are available. This figure demonstrates the overall trend of concentration near their export market, 85% of which is the UK, as so many activities are located in Northern Ireland near the ports and borders.

Figure 5. Mushroom stakeholders identified in Ireland (Mushroom producers: blue, substrate & casing: yellow, spawn: red, equipment manufacturers: green, representative bodies: purple)

Beyond the stakeholder mapping of Ireland, it is also important to discuss the strengths, weaknesses, opportunities, and threats (SWOT) to mushroom production in Ireland. For instance, the SWOT analysis of the mushroom production value chain has shown the following categories:

Strengths

1. The mushroom industry is the largest and most profitable horticultural sector in Ireland.
2. All materials used in the substrate manufacturing process are locally sourced.
3. Mushrooms can be produced year-round in Ireland at reasonable costs.
4. High quality cultivated mushrooms, mainly *Agaricus bisporus*.

5. High-tech. mushroom production companies and experienced mushroom growers.

Weaknesses:

1. There are very few specialty mushroom growers (oyster, shiitake and other exotics) in the Republic of Ireland.
2. There is a lack of skilled laborers and pickers in Ireland, with many workers coming from abroad to work on mushroom farms. Workers may need incentives to come to Ireland.
3. Mushroom marketing when compared to dairy and beef marketing in Ireland is poor.
4. There are only three producers of substrate for *Agaricus bisporus* mushrooms which does not allow for much competition.

Opportunities:

1. There are growing numbers of health-conscious consumers with demands for healthy, high-quality, and organic products.
2. There is rapid growth of the national and global mushroom market.
3. Oyster mushroom production is less complicated than Agaricus.
4. Abundance of agro-industrial wastes to use as part of the substrate to produce specialty mushrooms, thereby developing more sustainable and circular economic principles.

Threats:

1. The UK leaving the EU single market with no Permanent Deal in place which may disturb trade.
2. Number of mushroom growers is dwindling from 157 in 2005 down to 34 in 2020.
3. Straw incorporation schemes which require straw to be plowed into the ground instead of being baled and sold may see high demand for straw and higher cost of production of substrate.
4. Legislation regarding limiting the harvesting of peat that is used as a casing layer may reduce the capacity of growing *Agaricus bisporus* mushrooms, which as the majority of production, is a large threat to production.

In conclusion, while the Irish Mushroom Industry focuses on growing *Agaricus bisporus* mushrooms due to demand in the UK market and readily available supply of substrate materials produced domestically there is potential for growing exotic mushrooms such as oyster and shiitake if made affordable and marketed correctly. The mushroom production industry has seen steady growth in recent years despite Brexit which was thought to have a huge effect on the industry. This could still have impacts in the future, as the entire mushroom production industry on Ireland is set up to supply the British market, with many farms located along the border with Northern Ireland, poultry farms who supply manure to the substrate manufacturers, and the ports of Dublin, Belfast and Warrenpoint. It has been shown that there are threats and weaknesses to the mushroom production industry in Ireland. One important threat is that economies of scale are becoming the only way to run farms in the mushroom production industry. The cost per tonne of mushrooms produced is decreasing while the number of farmers is decreasing as well, with output increasing. There are only three suppliers of oyster mushrooms in Ireland which does not allow for much competition in the market with the consumer losing out as a result. While overall it is a threat to the industry by producing only one particular type of mushroom, it can also be an opportunity for many smaller farmers to grow a different variety and exploit the demand for different types of mushrooms by the consumer, that doesn't always want mass-produced products. Furthermore, the monopolization of mushroom production by large companies producing *Agaricus bisporus* is under threat, specifically because peat is used as a casing layer in growing *Agaricus bisporus* mushrooms in Ireland, the harvesting of which is currently subject to a long planning process in order to harvest over 30 ha sites. With peat suppliers now facing low supplies and the likelihood of importing peat from mainland Europe, it could be a great opportunity to switch to exotic mushrooms such as oyster or shiitake that don't require a casing layer to be grown.

5.2 Mapping of value chain agents in Denmark

Data for the Danish value chain analysis (VCA) was collected from the participating agents of the value chain through face-to-face and remote interviews by using a common semi-structured questionnaire (see appendix, Figure 1A for detailed questions). Tables 5 and 6 provide an overview of the different categories of value chain agents that operate within the Danish mushroom production context, with Table 5 listing the production agents, and Table 6 listing the auxiliary agents. We conducted field visits, interviews, and surveys to map out the value chain and gather new information to contextualize mushroom production experiences, challenges, and solutions. We collected surveys from a wide range of stakeholders in the mushroom value chain, from small-scale (<2 tonnes mushrooms/year), commercial scale (2-50 tonnes mushrooms/year), and industrial scale (>50 tonnes mushrooms/year) producers, as well as connecting with consultants and other interested actors such as substrate and spawn producers. There are also other stakeholders such as mushroom clubs, consultation firms, and private entrepreneurs, which have been identified from virk.dk, word of mouth, and through market research. The surveys and interviews conducted in Denmark revealed many perspectives across the value chain that are useful for interpreting the context from our VCA, as well as offering useful points of contact for planning valuable interventions.

Table 5. Overview of mushroom production value chain agents identified in Denmark

Mushroom producers	Categories	acTIVITY	Location	Region
hOEFYNS SVAMPE	Small-scale	Mush. Prod.	Odense	Syddanmark
FungaFarm	Commercial	Mush. Prod., Grow kits	Copenhagen	Hovedstaden

Bygaard	Commercial	Mush. Prod.	Copenhagen	Hovedstaden
Tvedemose	Industrial	Mush. Prod.	Lundby	Sjaelland
bEYOND Coffee	Commercial	Mush. Prod. Grow kits	Copenhagen	Hovedstaden
St. Restrup Champignon	Commercial	Mush. Prod.	Aalborg	Nordjylland
ØLSTYKKE CHAMPIGNON	Small-scale	Mush. Prod.	Ølstykke	Hovedstaden
Melholt champignon	Small-scale	Mush. Prod.	Hals	Nordjylland
VEJEN CHAMPIGNON	Commercial	Mush. Prod.	Vejen	Syddanmark

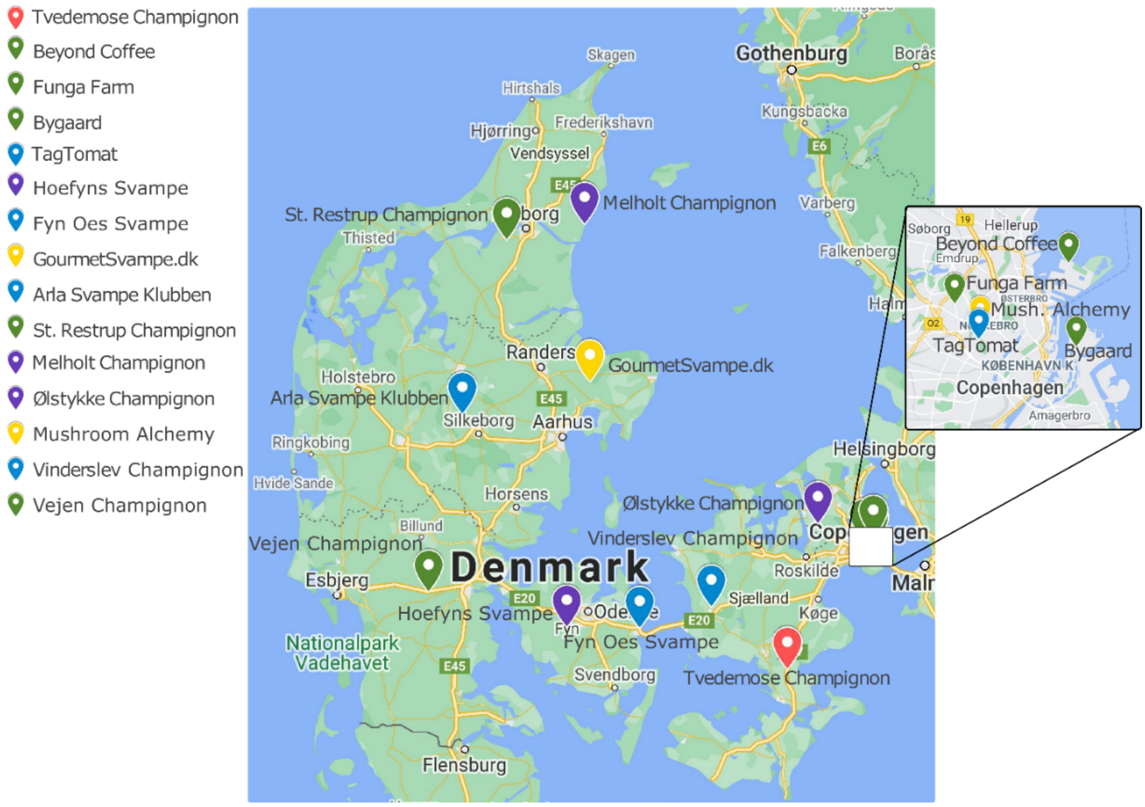
Table 6. Overview of auxiliary mushroom production value chain agents identified in Denmark

Mushroom Suppliers and Consultants	**Category**	**Activity**	**Location**	**Region**
FYN ØS SVAMPE	Consultant	Consulting, education, outreach	Nyborg	Syddanmark
Aarhus substrate startup	Consultant, Substrate supplier	New business models, substrate supply	Aarhus	Nordjylland
GOURMET SVAMPE	Online retailer	Grow-kit, culture, education	Pinstrup	Nordjylland
TagTomat	Brick and mortar retailer	Education, grow-kit supplier	Copenhage n	Hovedstaden
Mushroom Alchemy	Online retailer	Medicinal products	Copenhage n	Hovedstaden
VINDERSLEV CHAMPIGNON	Indirect	Mushroom infrastructure liquidator	Vinderslev	Midtjylland
Tvedemose Ejendom	Substrate supplier	Chicken manure compost	Lundby	Sjaelland

To better demonstrate the spatial orientations and potential interactions of the different actors listed above, we have mapped their locations throughout Denmark as shown in Figure 6. This figure shows that there is a relatively equal distribution of mushroom activities across the main regions of Denmark, Jylland, Fyn, and Sjaelland, with the highest concentration being in Copenhagen, which is unsurprising considering its high population density. Although there are two commercial producers on Jylland, and three on Sjaelland, there are none on Fyn, which is home to Denmark's third biggest city, Odense. There is only one producer on Fyn, which is a small-scale cultivator. Because of Denmark's small size, these activity zones are likely all connected to one another. For instance, based on some preliminary field data, we have noted that Vejen Champignon products are shipped all the way from Jylland to supermarkets in and around Copenhagen, a distance of 250 kilometers. A more thorough accounting in *Deliverable 1.3: Gap Analysis* will elaborate on the supply chain logistics around mushroom activities in Denmark.

Figure 6. Mushroom activities in Denmark as shown by the VCA. Legend is on the left, with corresponding locations detailed on the map. Copenhagen is zoomed in because of the high level of activity there. The legend illustrates that the red markers are industrial producers, the green markers are commercial producers, and the purple are small-scale producers; the blue markers are consultants or miscellaneous actors such as clubs; and the yellow markers are online or hybrid retailers.

Mushroom Activities in Denmark



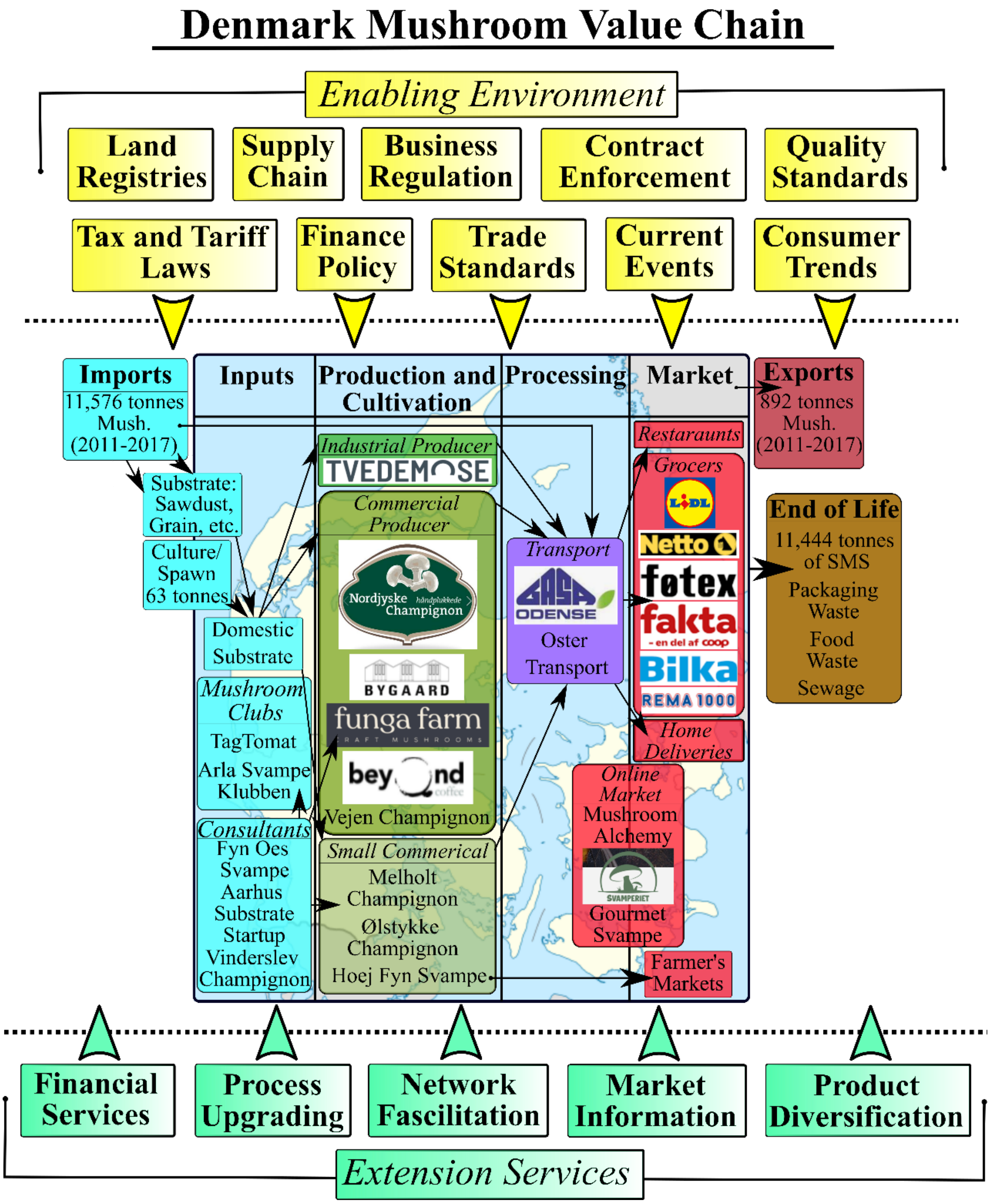
Furthermore, it is also useful to illustrate the productive capacities of some of the different actors in the Danish mushroom value chain, as seen in Table 7. These entries have been anonymized, and the data have been averaged to keep production information private, as per participant request. The range of producers in Denmark cultivated 100 kg a month up to 250,000 kg a month. We have listed both the production values, as well as the type of mushroom produced, where data were available. Altogether, considering the FAO's estimation of Danish mushroom production being around 4,000 tonnes a year, the data encompassed approximately 75% (3053 tonnes a year) of the domestic production market share in Denmark. The detailed survey accounts presented below of the actors described here in Section 5 can therefore be considered representative of the major conditions of mushroom production in Denmark. The issue of the weight of considering the different scales of operations from small-scale, commercial, to industrial production is an open question, one which we contextualize in the following sections. That is, what is relevant for one producer is not the same for another; the variety and nuance, combined with the necessity of anonymity, requires careful consideration of the challenges, solutions, and experiences outlined below for each section of the mushroom value chain.

Table 7. List of selected anonymized mushroom producers in Denmark with their associated production values per month, year, and what they produce. Data were derived from surveys. 'Yes' means production occurs; ND=no data on specific quantities produced.

Producer	Quantity per month	Quantity per year	Oyster per month	Shiitake per month	Lion's mane	Button	Other mush. prod.	Substrate
Units	kg/month	Tonnes/year	kg/month	kg/month	Yes/no	Yes/no	Yes/no	Type
A	100	1.2	100					Straw
B	500	6	Yes (ND)		Yes (ND)		Cinnamon Cap, Enoki, Maitake, Black Pearl Oyster	Grain/Wood
C	3000	36	900	900			Pioppino, King Oyster, Nameko	Grain/Wood
D	250,000	3,000	Yes (ND)	Yes (ND)		Yes (ND)	Enoki, Portobello	Horse and Chicken Manure Compost, Grain/Wood
E	800	9.6	Yes (ND)		Yes (ND)			Coffee grounds, Wood

With the categorization, spatial mapping, and demonstrative production of Danish mushroom actors in mind, we have designed the value chain map seen in Figure 7. This demonstrates the mushroom value chain in Denmark in visual format, with a few representative values to contextualize the flows of materials, as seen previously in Table 2 and 3. We have followed the standard VCA map template, as shown in Figure 2. The blue boxes in Figure 7 correspond to inputs, the shades of green boxes correspond to production actors of varying sizes, the purple box demonstrates a few examples of processors/transporters, the red boxes illustrate market actors of a variety of forms, with the magenta box showing the exports, and the brown box illustrating the end of life considerations. This final box is a novel expansion from Figure 2, as traditional VCAs oftentimes ignore end of life considerations; they normally focus on 'cradle to gate' or 'cradle to consumer' levels of analysis. However, we believe that expanding the scope is essential for identifying problems and solutions in a value chain, especially considering the contemporary importance of waste generation concerns and circular economic solutions. This is elaborated on in more detail in *Deliverable 1.3: Gap Analysis*.

Figure 7. Overview of the Danish mushroom value chain environment which consists of three components: value chain agents (center), enabling environment (top) and business and extension services (bottom).



For the sake of clarity, we have illustrated the mushroom value chain as moving linearly from left to right, from inception to disposal. Furthermore, we have conceptualized the mushroom value chain as an integrated whole spanning from inputs to end of life, which is supplemented by imports, exports products outside Denmark, rests on the expertise and assistance of extension services, and operates under the rules of the enabling environment. The first focal point, therefore, is on inputs; however, many of these inputs are imported. For instance, we show how Denmark imported 11,576 tonnes of mushrooms and 63 tonnes of substrate spawn per year on average from 2011-2017. Below this in Figure 7, the substrate and culture/spawn boxes are in between imports and inputs because although the majority are imported, some materials are domestically produced, such as copies of fungal genetic material (spores, liquid culture, etc.), even though the origins are almost always outside of Denmark, or crop residues such as straw. These domestic inputs are then combined with imports, such as wood pellets or sawdust from Germany, the Baltic states, or Sweden, to make the 'domestic substrate' input.

The consultants and mushroom clubs are listed as inputs because of the generation of demand via the latter, including for culture, substrate, and other equipment, while the former provides expertise or educational inputs. These inputs then feed into industrial, commercial, and small-scale producers. After production and cultivation via the listed companies in Denmark the products are shipped to a variety of sources, or have their products picked up by restaurants or other purchasers. One noted example of this is St. Restrup Champignon (Nordjyske handpicked champignon) which connects directly to Gase Odense, a very large distributer on the island of Fyn which then distributes the mushrooms across Denmark. The 'Online Market' box is situated between 'Processing' and 'Market' because the actors listed there take other materials, process them, and sell them on their own online marketplace. These webshops are places where more than just mushrooms are sold, such as extracts, powders, grow kits, books, posters, cultures, etc.

After processing and transport the mushroom products are sold on the market via a variety of outlets. For example, we have listed the most common grocery market outlets in Denmark, and these are places where we have gathered mushroom pricing data and information. Beyond online marketplaces, which we have already discussed, the major outlets are brick and mortar retailers; another example of market activity is shown by a smaller grower, Hoefyn's Svampe, who noted that they produced, processed, and transported their products to a farmer's market on Fyn, and were successful selling their products there. Furthermore, many commercial farmers connect directly to restaurants as their outlets. Other companies, like Bygaard, are well-known for their home deliveries, as they operate within densely populated areas, and utilize more common intra-city transport options, such as couriers. Furthermore, these noted different outlets also correspond to specific actors, such as producers, which leads them to specialize in particular avenues or areas. For instance, most of the mushrooms found in the grocery stores, for instance, are from Tvedemose, while many of the commercial mushroom farmers we talked to oriented most of their business at restaurants or personal deliveries; there are a few commercial farmers that sell to brick and mortar retailers, but the emphasis for some producers is on a high-quality product that is desirable by chefs or more generally for interested consumers. Beyond the domestic market, Figure 7 also shows that Denmark exported 892 tonnes per year on average from 2011-2017. These six examples of market activity, (brick and mortar, online, farmer's markets, restaurants, home deliveries, and exports) demonstrate just some of the potential means of delivering produced goods to consumers. Another indirect and unmapped delivery of goods is self-production by home-growers. The sale of DIY mushroom kits and cultures is very popular, and more people are growing the mushrooms they want to consume.

Furthermore, to broaden the scope of traditional VCA perspectives, and prepare for our *Deliverable 1.3: Gap Analysis*, we also included a representative 'End of Life' box which demonstrates a few components of mushroom waste generation associated with production activities. Because the largest mushroom producer in Denmark, Tvedemose, also makes their own compost for secondary decomposers, there are also massive water and energy inputs that go into this process, and therefore also generate waste, directly and indirectly. It is also critical to consider the embedded greenhouse gas (GHG) emissions or materials in imported products, such as what goes into processing wood into sawdust, or transporting substrate or culture across Europe. Beyond this, it is also important to recognize that along with mushrooms, SMS, packaging waste, food waste or scraps, as well as human waste are all produced concomitantly. As Figure 7 is primarily a generalized map, there are many more considerations elaborated on within this deliverable in later sections, as well as within *Deliverable 1.3: Gap Analysis*.

Above and below the Danish mushroom value chain shown in Figure 7 are the enabling environment and extension services, respectively. These interact with the Danish mushroom value chain via the symbolic dotted line, which is a 'membrane' through which specific avenues, such as legal channels, consumer perceptions, or consultant ideation influence relevant activities. As the Danish mushroom value chain does not exist in isolation, we included some examples of the extension services to show how the interacting, complementary aspects of the economy facilitate and allow successful mushroom production activity such as financial services, which are banks or credit unions; process upgrades which improves on existing methodologies to improve production or products; network facilitation, which improves connections between different aspects of economic activity; market information, which determines supply and demand assertions; and product diversification, which creates novel value generating activities, such as medicinal powders derived from over-supplied mushrooms. These are just some examples of extension services that are frequently mentioned in the literature, although many other services exist that contribute to the mushroom value chain in Denmark, such as free Municipal business courses offered for interested entrepreneurs.

The enabling environment is the context surrounding the mushroom value chain. This can consist of physical articles such as land, but generally consists of assumptions, regulations, or policies that define the scope, breadth, and nature of specific activities. These environmental enablers are, for example, tax and tariff laws, financial impetuses, current events such as the coronavirus, or supply chain issues. These different enabling environment boundaries effectively allow mushroom production to happen in its current form, as it enforces contracts and creates regulations for consumer safety that must be abided by. Other VCAs use enabling environmental parameters and extension service parameters to illustrate that any economic activity has underlying and overarching layers of activities that inform and allow successful operations. Therefore, the metabolism of Danish mushroom production occurs as a result of the interacting dimensionalities of the imports, exports, end of life, enabling environment, extension services, and the interior physical operations from inputs to markets.

5.3 Current practices and challenges in substrate procurement

One of the fundamental processes to conducting a successful VCA is to track the flows of materials through different value chain sections and actors. Two initial inputs that are fundamental to mushroom production are genetic material (spores, liquid culture, mycelium, or spawn for example), and substrate with which to feed and grow the genetic material on. The initial material flow in mushroom production that we focused on was substrate production and utilization. In this regard, a primary result from our previous section, which was supported by our surveys, revealed that there are no industrial substrate producers in Denmark; this means that there is high-risk of supply chain issues, and high embedded GHG emissions associated with transporting large volumes of materials (oftentimes, the smallest possible order size for bulk substrate is 21-25 tonnes). Although some companies produce their own substrate, such as that composed of coffee or wheat straw, most other sources of substrate come as imports from other countries.

One notable exception is Tvedemose, the largest mushroom producer in Denmark, which uses around 200 tonnes of horse manure per week acquired in Denmark from approximately 1,000 horses from stud farms and riding clubs to begin its composting process for their secondary decomposers, button mushrooms (*Agaricus bisporus*). These manure sources are located on Sjaelland, the island where Copenhagen is located. Their first step for composting involves mixing the manure (which is also composed of chicken manure) with straw, and subjecting the mixture to a specific wetting and temperature conditions for optimal composting.

They also use sulfuric ammonia and lime to adjust the pH (>10) to its optimal range. For their organic production, they use gypsum, lupine seeds, and wheat bran for this process instead. After initially composting, Tvedemose moves the compost to a wind tunnel at 58 C air for six hours, which kills any unwanted fungal spores that could contaminate the compost, as well as undesirable bacteria. This also removes the ammonia via evaporation. When the compost temperature has been reduced down to 20 C, desirable fungal spores are added, then it is left at 25 C for 20 days to mature into usable substrate. Tvedemose uses sphagnum moss, lime, and water as their casing layer because they contain the necessary bacteria that induce fruiting. At this stage there is approximately 100 kg/m^2 of substrate with a depth of 20 cm. Tvedemose notes that they do not use any pesticides or sprays to keep unwanted competing organisms out; however, they note that this spraying was done 30 years ago, because production periods for fruiting were 60-90 days, when now it only takes 14 days of fruiting with the optimal temperature and materials. Directly after harvesting, the mushrooms are cooled to 2 C, and are supposed to be on the shelves of stores within 2 days. In this regard, they note that temperature stability is key for shelf life. Tvedemose harvests multiple flushes for 2 weeks, after which the cultivation room is heated up to 70 C with steam for sterilization purposes. The room is then emptied, cleaned, and readied for the next day when a new batch is added. Overall, the entire production process takes 10 weeks per batch (70 days).

Tvedemose also lists some activities they undergo regarding sustainability issues that are a response to the necessities of climate change. The noted activities are recycling of all the water that is used for washing mushrooms, which is reused for the composting input; installing a heat pump, which has reduced their CO_2 emissions by 40%; engaging in waste sorting; heat-sanitizing all organic waste, including SMS, and using it as soil amendment; and changing to LED lights which has reduced power consumption by 10%. Regarding circular economic principles, Tvedemose states that they are working to close their production loop more completely, as they are currently throwing away around 5% of their entire production due to bruising or other topical marks. After production, Tvedemose sells their SMS as a soil amendment to horticulturalists, while also using it in their own production activities. They note this is done to avoid using fertilizers in their other production activities. This is a good illustration of synergies between waste generation in one economic activity into utilization as an input into another. However, this is only made possible because Tvedemose is a large industrial production company that has the commercial capacity to utilize these streams, as they produce a diversity of agricultural products beyond mushrooms. Beyond production, they also have some particular motivations around sanitation with specific consumptive habits in mind: for instance, they believe that it is very important for the consumer to be able to eat the mushrooms raw without fear of sickness.

Although there are no industrial producers of substrate in Denmark, there is a widely produced substrate input that is underutilized in mushroom production: straw. This was supported by our interviews, in which one of the small-scale producers identified straw as easy to use with very little processing required, especially when paired with aggressive hardy fungal species such as *Pleurotus ostreatus*. They noted that, even at the end of the cycle, after one or two full flushes, there was no evidence of contamination by other microorganisms with straw. When they shifted to sawdust, however, they experienced mold incidence, which had not occurred while using straw. The simple and effective combination of straw and oyster mushroom has the potential to be imitated by other small-scale producers, if they are interested, as there is a potential wide availability of straw as a substrate source, with about 3 million tonnes produced annually in Denmark. One of our stakeholders also identified the price they paid for getting organic wheat straw: 26.67 Euros per bale with dimensions of 1.5m x 1m x 1m. However, another stakeholder noted the difficulty in getting access to organic products; although in Denmark it only takes three years to transition from conventional to organic practices to get accredited, they still noted a dearth of available organic straw or grain materials, and claimed that conventional materials were much easier to find. Furthermore, year to year variation was high when it came to availability: a source from the previous year wasn't necessarily guaranteed for the current year. Interestingly, one of our stakeholders noted that there is a list of materials that cannot be marked as organic, such as horse manure or wood products, but that final products grown on them can themselves be called organic, according to the rules. They also noted that they use wood pellets that are marketed for use in burning as a substrate input. They note that the source can potentially label with around 99.9% accuracy what species of wood that the wood pellets are composed of, which is essential for mushroom growing.

Mushroom producers in Denmark are very aware of the risks of relying on external substrate production, and some have undertaken steps to address this. One example is using coffee as a substrate, which has been locally sourced from cafes and canteens domestically. Furthermore, this company, Beyond Coffee, has done experiments with Kobenhavn Kommune on the use of two organic portions (food waste and garden waste) of municipal solid waste (MSW) as a viable substrate source for oyster mushroom production. Their results were consistent with previous research: the oyster mushrooms could successfully colonize and fruit on the organic MSW, but there is much labor that goes into processing the MSW into the appropriate substrate that is sanitized, has a homogenous appropriately sized particle, and has a moisture content necessary for production. Their biggest challenge was processing the material into the appropriate particle size, as the MSW ended up being too large; this high surface area to volume ratio is not ideal for moisture retention, and they posited that this could explain the low yields, which were not satisfactory from the perspective of their economic imperatives. However, the yields could be more acceptable for smaller scale producers or farmer's market sellers. This same sentiment was reflected by other producers who noted that shredding the MSW, straw, or biowaste was one of the biggest hurdles to achieving high-quality substrate that is composed of lignocellulosic waste, biowaste, or organic MSW.

Another similar issue was identified which concerns the importation of colonized substrate where the mycelium has already succeeded in colonizing the substrate completely. This ready-to-fruit system reduces the infrastructure needed for inoculation, pasteurization, packaging, and genetic material procurement by producers in Denmark. However, it is also critically vulnerable to supply chain disruptions and price changes. Ultimately it was concluded by the stakeholder that a similar methodology but supplied via local production within Denmark would be ideal; this specialization of method (separating within-production activities into discrete companies for substrate production, culture development, inoculation, mycelium running, and fruiting, for example), has evident market advantages, at least until supply chain disruptions incur major costs or interruptions to downstream actors. Relying on imports also has another consequence: there are unknown components as a result of differing international standards. For instance, an interviewee stated that Germany has relaxed rules about the types of wood that can be used for sawdust production: painted wood is allowed to be used for this purpose, which ultimately means that mushrooms can take up any of these contaminants which can be passed on to humans. Sweden was noted to have a very high-quality product which was legally required to be clean of all petrochemicals, including paint, and which also had a 99.9% species guarantee. This is not surprising given Sweden's comparative advantage when it comes to forestry (68.7% of land is forested). Despite this import-reliance trend for woody-decaying mushrooms, one of our interviews connected us with a startup in Aarhus, Denmark, which is focused on supplying substrate domestically. The reliance on imported substrate materials, which has been identified by stakeholders in our interviews as being problematic, especially given supply chain crises such as Coronavirus, is therefore beginning to be redressed. Considering that the majority of secondary decomposer producing companies use compost, which is mostly produced domestically, startups would be able to focus exclusively on wood, lignocellulosic waste, biowaste, or MWS transformations for primary decomposers.

Beyond material flows, it is also important to consider the cost indices for mushroom substrate use. For instance, market research has identified prices for substrate sold on the market. The quantities are usually in the range of 0-150 kgs and are therefore not considered truly bulk values. For instance, a company called Northspore sells substrate, at full bulk discount, for 7.12 Euros/kg. This price is the same for both substrate composed of grain and for wood. Another company, called Gluck Pilze sells substrate at a full bulk discount for 4.37 Euros/kg for wood, while for straw it is 11.9 Euros/kg. A third company, called Out-Grow, sells wood substrate at 6.89 Euros/kg and straw substrate for 11.47 Euros/kg. A fourth company, Bio Myco Tec, sells sawdust at around 19 Euros/kg. A bulk supplier, called Agaris, which operates in many European countries, sells substrate for around 1.5 Euros/kg. However, they do not sell quantities lower than 21 tonnes per shipment. This therefore excludes this as a viable opportunity for any but the largest industrial producers. Furthermore, an interview with a stakeholder identified a standard bulk market price of around 1 Euro per 1 kg of substrate, which was identified via their own market research. These prices are comparable to the 1.93 Euros/kg of substrate which was paid by Danish companies in TP-B (2011-2017), which we derived from Statbank information.

5.4 Current challenges for spawn creation or acquisition

Beyond substrate, the reliance on imported spawn, mycelium, and liquid cultures, such as from one of the biggest suppliers in Europe, Mycelia (mycelia.be), has been identified by partners as being a crucial supply chain issue. For instance, during the Coronavirus, although Mycelia direct supply was not impacted, the supply of their inputs was impacted, and they passed on this increase in prices to their purchasers, which in turn drove up the cost of producing mushrooms in Denmark. Furthermore, it was noted that on an order costing 600 Euros, about 200 Euros is for transportation, as the mycelium needs to be refrigerated. This is a potential supply chain issue, as total reliance on imported sources for a fundamental mushroom production input is high-risk. There are also associated high GHG emissions with transporting goods so far, especially when refrigerated. Furthermore, one stakeholder, who sells organic liquid cultures in Denmark, noted that the origin of all their cultures came from imports. They had successfully cultured one native species of fungus from Denmark, an oyster mushroom, but are still working on getting this ready for market. Reducing emissions, improving supply chain integrity, creating jobs in Denmark, and distributing reliance on inputs outside of large industrial entities necessitates a shift in the current supply of fungal genetic material in Denmark. This has relevance for activities beyond food production, as mycoremediation and medicinal mushrooms are a high-value underutilized source of benefits for society and the natural world in which it is situated.

5.5 Current challenges for spent substrate valorization

Another interesting supply chain dynamic is the lifecycle of SMS after it has been used to produce mushrooms. For instance, one of our interviews 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 rate 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, and some countries such as Brazil struggling to fill orders for 2022 [60]. Another advantage of using SMS is that 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 only after hemicellulose and lignin by mushrooms. The high level of carbon in SMS is compatible with the humus layer of the soil, as it improves soil moisture retention, organic carbon, and retention of nutrients via steady state dynamics. In one 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.

5.6 Economic context of mushroom production

One primary challenge for mushroom production in Denmark, and correspondingly the study of this value chain, is the competitiveness of the market, which can be described as highly technical with siloized actors and closely guarded information. However, although stakeholders were reticent to share financial information, such as that concerning cost or prices, Denmark has public information on all registered companies (virk.dk). Figure 2a in the appendix outlines some example financial data from a few different mushroom producers from commercial to industrial, and also for a supplier of inputs. The financial information offers a valuable quantitative lens to identify the different scales of production activities and their interaction with wider institutional and external factors. For instance, these documents are written as public letters to shareholders, and as such address company operations; they are therefore not simply quantitative, but are also explanatory and contextual in nature. For the sake of clarity, we have included some essential statements that each company has made during their most recent year's letter to stakeholders. This is seen in the '2019-2020 Comments' column in Figure 2a in the appendix. These comments help explain the values as they are presented by providing much needed context.

For instance, one of the most important contemporary impact factors identified from these documents was the Coronavirus pandemic, which has stressed supply chains, necessitated different patterns of consumption, and interrupted flows of materials. Mushroom production, which as a result of being a delayed production process (from start to finish around 40-70 days) is a planning-heavy operation, has particularly vulnerabilities to abrupt changes, such as lockdowns or consumption reductions. For instance, Beyond Coffee, which has a very innovative business model where it upcycles coffee ground 'waste' into valuable mushroom substrate, had a net loss in 2020, due to the lack of coffee ground availability, as lockdowns and reduced patterns of consumption produced less coffee waste. Bygaard and Tvedemose's substrate supplier also struggled as well due to the Coronavirus; Tvedemose and Funga Farm, however, were both profitable. These documents show that the mushroom production business is incredibly sensitive to the surrounding context in which they operate, such as financial or health-related crises. Year-to-year variation is also high concerning profits or losses. One of Bygaard's specific comments concerning Coronavirus noted the lack of traffic due to lockdowns and changes in consumption habits as being particularly impactful to their operations. One response to the comments like this as shown in Figure 2a about the lack of traffic due to the Coronavirus could be the expansion of online markets, or the utilization of a common marketplace app where sellers can connect over-produced products with willing customers. This would not require producers to have brick and mortar retailers, which have high costs due to their necessary locale in high-visibility, and therefore high cost, areas to move their goods. This is a potential intervention point which can be addressed via *Task 4.2: Development, deployment of the data-driven MUSHNOMICS digital platform.*

Although mushroom production is generally considered an economy of scale, it is worth looking further into this assertion based on the data in Figure 2a. For instance, averaging the number of employees for each of the four mushroom producing companies listed in Figure 2a shows the following in Table 8. Tvedmose, which produces around 3,000 tonnes of mushrooms per year and correspondingly generates 3,771 Euros per employee, while the other profitable listed company, Funga Farm, generates 8,008 Euros per employee over the year. Therefore, a specialist company that produces high quality products has double the profit generation per person than the largest mushroom producer in Denmark. As this is only a single comparison, it should not be considered representative, but it is important to note, especially concerning multiple interviewees identified a very specific market for high-quality primary decomposer product compared to mass-produced secondary decomposers. There is therefore room for expansion in niche markets that specialize in particular functions, while also being localized. However, Table 8 also shows that the personnel costs, or the payments to employees, were higher for Tvedemose at 21,848 Euros/person/year, by a significant margin, compared to the other companies. Even if we add the profit generation per employee Funga Farm's takeaway payments were only around 12,336 Euros per person per year. This metric only estimates these payments, as it averages the number of employees over a year; because there is no information on specific duration of each employee (or whether it was part-time or full-time), this could reflect seasonal peaks or valleys, and could therefore explain the variation in employee payments. It is worth considering these results within the context that there is an appeal by small producers to work for themselves, to obtain the profits of their labor and not become alienated from their efforts. Therefore, monetary comparisons are not the only useful metric.

Table 8. Profit generation, employee context, personnel costs, and payments for companies listed in Figure 2a (appendix)

Company	2019-2020 profit (Euros)	Average no. employees	Profit generation per employee (Euros)	Total Personnel costs (Euros/yr)	Payments per employee (EUros/yr)
Beyond Coffee ApS	-74,267	8	-9,283	55,333	6,917
Funga Farm	16,016	2	8,008	8,655	4,328
Tvedemose Økologi ApS	588,289	153	3,771	3,408,332	21,848
Bygaard ApS	-14,311	2	-7,156	3,026	15,132

Furthermore, it is also worth mentioning that although there is a potentially large knowledge or technical hurdle involved in mushroom cultivation, our interviews identified that there is also a correspondingly high profit margin, up to around 30-40% of input materials cost. This indicates that the market is nowhere near saturated. Although current monopolization trends or incredibly large market cap exploitation by a few large companies that can afford to lower their prices (pricing out competition) even at a point of temporary losses is real, the existing context where there are multiple markets—online, brick and mortar retail, restaurants, exports, home delivery, and farmer's markets—including specialization of product such as mass produced button mushrooms or high quality primary decomposers, there is room for coexistence, specialization of function, and diversification of scales and market shares. This is especially pragmatic in Denmark, which has a very high population density, population connectivity, many avenues of delivering product to markets, and a small-business friendly enabling environment. Furthermore, as is discussed in Deliverable 1.3, there are massive amounts of useful mushroom inputs that are produced in agricultural activities in Denmark every year which could ideally allow small scale operations to flourish, especially if they are located in close proximity to crop residue producers and utilize this substrate input.

It is also important to discuss the likelihood of bankruptcy and its relationship to impacting markets, including overall market health. For instance, in 2018, the Danish company Egehøj Champignon closed due to a specific mold that infected their compost pile, which was itself a food contaminant and infected the secondary decomposing mushrooms grown on it. Unfortunately, the mold became endogenous and its spores were lodged in vents and airways, so even after a temporary closure with an intense cleaning of infrastructure, when the composting was reactivated, the mold returned. They were forced to close because they had no feasible way to import the large amount of compost required to produce mushrooms. Before their closure, Egehøj Champignon supplied over 50% of the total domestic production of Denmark. It was expected that the remaining mushroom producers would simply absorb this demand, with rising prices cushioning the cost of expanding their infrastructure. During this closure, it was the opinion of one of the largest purchasers of mushrooms in Denmark, Gasa Odense, that they did not expect any new mushroom farmers to emerge in Denmark, and they stated that they assume that "the two remaining farmers (St. Restrup and Tvedemose) will cultivate more mushrooms to compensate for this. With mushrooms, there is a long start-up phase. You need to be very knowledgeable to grow mushrooms. There are also a lot of expenses" [61]. However, this specifically discusses the production of secondary decomposers, such as button mushrooms. The startup time, knowledge required, and technical infrastructure can be significantly less for producing woody-decaying mushrooms such as oyster or lion's mane. Therefore, it is this particular production process which relies on industrial composting which is highly vulnerable; other methods are not nearly as vulnerable and require fewer inputs to get operations going. This is not to downplay the challenges of primary decomposer production. Nonetheless, it is, for instance, possible to purchase inoculated, spawn-run bags that are ready to fruit; therefore, with only climate controlled areas, mushrooms can be produced with little upfront costs or technical inputs. The primary question then becomes one of scale and risk assessment.

It is also worthwhile to complete the story of Egeholm Champignon. When they were faced with closure, they restructured in 2019 as a cannabis-producing company, Atlas Biotechnologies, with a Canadian headquarters [62]. The transition was possible because Egeholm Champignon has 19 climate controlled rooms which were considered ideal for cannabis production. It was noted that this new activity will eventually employ around 100 new people. This is relevant to the discussion of a mushroom VCA because it shows how the physical infrastructure is suitable for many different productive purposes, even as production methods, or consumption patterns, shift or evolve. For instance, the climate controlled chambers could also be ideal settings for other kinds of plant production, such as edibles like tomatoes, cucumbers, or leafy greens; furthermore, other medicinal plants, which have a much higher price per kilogram, are also options. Therefore, any suggestion for developing mushroom production infrastructure is not necessarily a high-risk endeavor, as it has potential downstream re-applications.

This section has detailed some of the challenges and successes of mushroom producing companies in Denmark. Although there can be hurdles to compete with already established companies that exploit economies of scale, there are a large number of small-scale mushroom farms on the rise in Denmark, supplying specialty as well as standard products at competitive prices. The struggle of small-scale local producers was elaborated on by an interviewee, when they noted that when they were trying to sell goods to a distributor, the distributor was only interested in connecting with the largest mushroom producer in Denmark; the selection of mushrooms (oyster, button, etc.) was considered an afterthought, and not a primary concern. This also speaks to the emphasis on quantity over quality, as mass-produced mushrooms are not the best quality items. Because of consumer standards, the product emphasis is on uniformity, not on quality. Furthermore, there seems to be a link between size of the endeavor and the targeted consumptive markets: for instance, small scale producers struggle to supply to restaurants, and often rely on farmer's markets and private orders. Medium or large-scale operations have more reliable week-to-week production thresholds that allow for repetitive order completion, including to restaurants and grocery stores. They also have a very uniform product which is essential for the highly-homogenous standards of restaurant or supermarket products. There are also indirect benefits produced by small-scale producers compared to huge economies of scale operations: one stakeholder noted that the siloization of actors along the mushroom production chain is not synergistic. It was emphasized in an interview that it was the local small-scale producers, or even the clubs and consultants, who are the ones getting facetime with customers, answering their questions, inspiring interest and increasing demand for mushrooms and related products; the large companies are opaque and thrive off this interest generated via small-scale actors. Furthermore, this issue of scale is given with the context that the likelihood of catastrophic microorganism contamination is much higher with large-scale operations than smaller ones; these catastrophic occurrences have a much larger market impact, as indicated by the 2018 collapse of Egehøj Champignon. Therefore, distributing production, especially of niche production efforts, can effectively buffer against these risks. It is also worth mentioning that there is currently an undersupply of wood-decomposing mushrooms, as the current supply is primarily of button mushrooms. There is therefore a large demand gap that can be filled by increasing oyster, lion's mane, or shiitake mushroom production. Furthermore, the widescale reliance on imported inputs can be redressed via localized utilization of existing resource flows in Denmark, which we identify in *Deliverable 1.3: Gap Analysis*.

5.7 Challenges for logistics

Another challenge identified via our interviews was the connection between producers and clients. There are a variety of methods currently in use by companies to receive orders and communicate, such as email, phone, text, and social media such as Instagram messaging or Facebook groups. The precise scheduling of delivery of mushroom products that can vary by +/- a few days for harvest is a challenge, and logistics have been identified as an issue by producers. For instance, this delivery calculation determines how producers decide on whether to accept new orders based on past fulfilments, etc. These issues could be an ideal place to situate interventions in the form of a user-friendly app that can help facilitate order creation and fulfilment. Furthermore, another crucial identified issue with supply and demand was the potential for overproduction with no existing orders to deliver to. Having an ad hoc solution would benefit many growers, who simply need to be able to reach out to a digital market, which is composed of many interested mushroom buyers, when they have an excess that is fresh and needs to be sold as soon as possible. These issues are all compatible with digital platform development as a potential solution.

Concerning logistics, Denmark has the advantage of being demographically and geographically advantageous for localized production, distributed via small-scale operations ideally adding up to meet local consumption of mushrooms in Denmark and replacing a reliance on imports that have high GHG emissions associated with transport. For instance, compared to the rest of Scandinavia, Denmark has a per capita population density of 133.9 people/km^2. Finland, Norway, and Sweden have values of 16.6-22.5 people/km^2. For comparison, the population density of the USA is 36 people/km^2. Therefore, the demographics of Denmark make the logistics necessary for the goals of distributing production and connecting suppliers and producers achievable, especially compared to other less population-dense countries. Concerning supply-side dynamics, there were some interesting points of potential intervention or intentional planning that could fill demand gaps. For instance, one of our small-scale stakeholders identified a total (besides them) lack of local producers on the entire island of Fyn, where Denmark's third largest city is, Odense. As Denmark is a small country with a high population density, this is not a critical issue, although prioritizing localized production could nonetheless be beneficial. There is also a very large gap in the supply of oyster, shiitake, or other wood-eating mushrooms in supermarkets, which primarily carry secondary decomposers such as portobello or button mushrooms. This is a prime situation where localized production of primary decomposers could fill existing needs while also fulfilling important circular economic criteria, especially considering that oyster mushrooms grow very easily on straw, which is produced by the millions of tons in Denmark every year.

In a similar vein, concerning supply and demand challenges, given the large amount of planning that goes into cultivating mushrooms without necessarily having a guaranteed market output, a few points were identified in the interviews. For instance, it was noted that mushrooms have the advantage of having pluripotent uses, from medicinal to edible. For instance, a single mushroom species, such as lion's mane, can be used as a regular edible mushroom, but it also has medicinal properties, such as being neurogenic. Therefore, producers who cultivate lion's mane have noted that it offers the advantage of being usable as a shelf-stable powder or extract, which can be selectively utilized as a pathway to move inventory given an economic downturn where consumption lessens, or when they produce too much, and it cannot immediately be sold while it is freshest. It was also discussed, in a similar fashion, how other mushrooms could still have much utility via being ground into powders, or turned into culinary stocks, such as for soups. This could be a valuable shelf-stable product given the powerful, unique umami flavor profile of mushrooms, which is retained via drying or minor processing into stocks, although this is significantly less valuable compared to medicinal mushroom products.

5.8 Policy and institutional framework

On the policy side, one of our smaller-scale producers identified two informational stopgaps: the first was on the bureaucratic side, which involves the paperwork necessary for business registration and inspection rules. Denmark is known to be one the most accessible nations when it comes to opening a small business, with low registration fees and institutional hurdles. However, they also have a very high small-business failure rate of 58% after five years [63]. There are therefore steps that need to be taken from a policy side to encourage the solidification of business endeavors to encourage continued productivity. For instance, we saw that on virk.dk, for a single page of existing mushroom companies, at least 5 pages for discontinued companies existed as well. Secondly, there are also unclear rules about the classification of medicinal products, which impacts the marketing of mushrooms grown for this purpose. However, both of these issues were identified as not being insurmountable.

Another important policy, or 'enabling environment,' perspective is that Denmark is one of the most expensive countries to live in in the entire world, being in many cases in the top 5-10 countries on many statistical lists [64]. Accordingly, one of the biggest burdens associated with any business activity in Denmark is the cost of real estate, and paying the other costs associated with this, such as utilities, maintenance, and capital depreciation. This can be a large hurdle that is prohibitive to small businesses operating in Denmark. Although stakeholders have noted that Denmark is business friendly in many ways, such as having free business courses and low registration costs, because of how expensive it is, finding real estate is a critical issue. For instance, one stakeholder mentioned that they have spent over 100 hours just trying to find a suitable location for their business. They noted that they had contacted farmers and others who have available productive space, but noted that the space is competitively leased, and it often went to carpenters or other skilled craftsman who could afford to pay more in rent. In response to this, our interviews identified that some small-scale mushroom actors chose to operate outside of cities, from their homes, or focused on utilizing a webshop to sell their product or offer their services. Usually, this small scale meant that these services or products are marketed and sold to individual customers, although multiple actors expressed a desire to eventually grow product for restaurants, once they scale their operations. There was also discussion about the realities of entrepreneurial burnout: although these stakeholders are passionate about mycology and mushroom production, there are limits to what this can accomplish without assistance from governance structures or policy incentives.

Another small-scale stakeholder discussed the difficulties of starting a business, even if that activity addresses a very specific evident need. In this case, there was discussion on the justifiability of starting a substrate-production company; the stakeholder noted that most people they talked to were not concerned with international reliance on imported bulk goods, such as substrate. Supply chain fluctuations, disturbances as a result of the Coronavirus pandemic, or the likely implementation of a carbon tax that would heavily impact transportation costs were of little concern; however, these issues are likely to become more severe, and will hopefully garner enough merited attention in the future. Because of these factors, and the evident need to supply substrate for mushroom production on a large scale (around 37,000 tonnes of substrate are used every year in Denmark), this stakeholder also noted that the scale of production didn't necessarily have to be hugely industrial or run by a single entity: because of the existing demand, they noted that competition from other substrate makers would be welcome, as it would distribute activities in closer proximity to their end-points, while also allowing room for development and trialing new methods. There was also discussion, from multiple stakeholders, about the interesting disconnect between Danish cultural values of being an agricultural-exporting country while importing 75% of the mushrooms they consume. This is in stark contrast to Denmark's agricultural total import:export ratio which is 10,616,000,000 Euros to 15,832,000,000 Euros for all activities overall [65]. Denmark therefore usually has 50% more exports than imports in monetary terms, instead of having 133% more imports for mushrooms. This is a critical gap that can be addressed in many ways, which includes utilizing existing substrate sources that are produced domestically, which is discussed in *Deliverable 1.3: Gap Analysis*.

Finally, multiple stakeholders have noted that Denmark needs to move faster concerning market capitalization, as the market for mushrooms is currently booming, just outside of many people's radar, according to interviewees. This is not just for food-related mushrooms; there are also real applications and markets for medicinal and mycoremediating fungi as well. Having the domestic capacity to culture, spawn, cultivate, and reproduce valuable fungi is a critical market need, especially considering fungi's application in plastic digestion, or other petroleum products, as well as forever chemicals such as PFOAs [66]–[68]. As the previous paragraph also mentioned, interviewees have experienced a lack of interest by municipalities and other similar bodies when it came to these concerns reflected in this VCA. The institutional framework can therefore afford to be improved in order to capitalize on the 'green revolution' trend that many Danish producers and consumers are promoting and engaging with. There are also other examples of this, such as mushroom clubs in Denmark, one of which was just formed at TagTomat in downtown Copenhagen. There are therefore crucial elements already present in Danish society necessary for increased mushroom cultivation to be a success, both in an abstract sense, such as for cultivating microorganisms for future applications, and in an immediately relevant material sense, as a source of food and medicine. There is also the desire for localized food production, especially products that can replace meat, one of which is mushrooms; there is a recognition that supply chain issues are real and increasing in importance; and there is a recognition that mushrooms are not just food, but also have socially beneficial application. Having a thriving mushroom production chain from supply all the way to end of life processing would create downstream synergies such as having the ready capacity to exploit cultivating other types of fungi for medicinal, industrial, or mycoremedial purposes.

6 Conclusions

The results of our VCA, which derived data from our literature review, databases, interviews, surveys, and field visits, demonstrated the quantitative flows of mushrooms and related materials in Denmark, Ireland, Hungary, and Romania. We showed that Denmark is the only country with a negative trade balance, as it consumes more mushrooms than it produces. This was not a trivial amount: over 6,000 tonnes of mushrooms were consumed than were produced per year on average from 1996-2020 in Denmark. Beyond quantitative flows of mushrooms in all consortium countries, we also looked more closely at the Irish and Danish mushroom production environment. We discussed essential logistical, technological, or institutional enablers and boundaries to successful business operations using a SWOT analysis. We also identified the high degree of sensitivity of mushroom production to changes in consumption, demand, and market flow based on outside factors; for instance, the biggest impact, according to the producers in Denmark, was the Coronavirus, which disrupted supply of key inputs, such as coffee grounds, which were consumed in much smaller amounts given shutdowns and recessionary fears.

To avoid future supply chain tensions both internal and external, such as catastrophic closures from microbial contamination or Coronavirus impacts, it can be concluded that small-scale localized production in the future should be encouraged, as well as differentiating production into other exotic mushroom species that utilize different feedstock sources and are simple to grow. Danish financial data has shown that it is possible to generate value for employees and remain profitable as small-scale or commercial producers, even in competition with industrial producers; furthermore, small teams are capable of producing commercial levels of mushrooms (2-50 tonnes per year). Our interviews have also shown that Denmark has many of the institutional laws, demographics, geography, and market pressures (high mushroom consumption domestically) necessary to expand local production. A similar finding was found in Ireland, whereby there are opportunities for responding to restrictions on peat farming (a critical secondary decomposer casing material) via developing exotic mushroom production. Furthermore, as indicated by our interviews, who also reflect on the consumers' habits that propel their industry, Denmark has a 'green revolution' movement that is quickly gaining momentum; this movement is concerned with high-quality, healthy, locally produced, and circular products. Ideally, the results of this VCA, and the further achievement of MUSHNOMICS deliverables, can allow our stakeholder group to collaborate and form a community with as many stakeholders as possible to try and improve their access to resources and markets with our digital platform, which will address the real supply chain issues addressed here in this report.

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9 Appendix

Figure 1a. Collection of survey tables used for interviews with mushroom value chain actors. The four tables are Mushroom Production, Substrate, Challenges and Solutions, and Supply Chain Role.

A)

Mushroom Production									
Question	***Answer***								
What are the species grown?	Total	Oyster	Shiitake	Lion's mane	Agaricus bisporus	Grow-set	Grow-box	Culture	Medicinal
Medicinal and/or edible species?									
What is the production of mushrooms per week?									
How much (kg) are you selling per week?									
What is the selling price of each species per kg?									
How many shipping containers are in use for spawn running?									
How many shipping container is in use for production phase?									
Number of trays or grow bags per container for production phase?									
What is the total growing area (m2) you have?									
What are the mushroom yields per m^2?									
Products sold: edible/medicinal mushrooms, grow bags, equipment, culture?									
Price per unit sold for the above									
What is your general cost of production per species/kg?									
Whom are you selling to? (Supermarkets, Private people, Restaurants)									
Do you export your products?									
If yes, how much?									

What is selling price of exports (per unit, kg, item, etc.)									

B)

Substrate				
Question	***Coffee grounds***	***Sawdust***	***Compost***	***Biowaste (agri., house, industry)***
What is your substrate used?				
What is the substrate quantity you use per week?				
Who supplies it?				
What country does the substrate come from?				
How do you acquire it (delivery method)?				
What is its cost/kg of substrate?				
What do you do with spent mushroom substrate (SMS)?				
What does it cost you to dispose the SMS				
Is there any provision from the commune to handle SMS?				
Do you import or export substrate?				
If yes, how much?				
What is the unit price (kg, unit, etc.) of export?				
Can you think of other agricultural and municipal wastes, that could be used as substrate?				
Do you prepare your own substrate?				
What are the different steps from substrate procurement to spawn running? (sanitizing, water addition, stabilizer treatment to augment pH, etc.)				
Are there other substrate sources you are interested in?				

C)

Current Challenges and Solutions		
Question	***Challenge***	***Solution***

What are the current challenges for substrate procurement?		
Culture procurement?		
Health/disease/spoilage?		
Delivery of goods?		
Ordering by clients?		
Sale volume (too much, too little?)?		
Pricing issues?		
Logistics/delivery issues?		
Opportunities for scaling?		
Governance/food regulation/inspections/barriers to production?		
Are there supply chain issues or shortages you experience?		

D)

Supply Chain Role	
Question	*Answer*
Do you use apps, online, email, paper, phone for orders?	
How do you meet order requirements?	
How do you rate the interconnectedness of the supply chain?	
Availability of materials used for inputs?	
Are there supply chain gaps?	

Figure 2a. Publicly accessible financial data on selected mushroom production actors. Data available at virk.dk.

Company Name	Website	Company Type	Size	Categories	Values	Values	2019-2020 Comments
Beyond Coffee Aps	**beyondcoffee.dk**	**The purpose of the company is to conduct the trade and production of mushrooms and related activities.**	**SME**		**2020**	**2019**	The company lost more than half of its shar capital at the end of the financial year. Management expects to restore equity throu positive earnings. The company is in concret negotiations with external investors about a capital injection that will restore the share capital. The company's profit and loss accou for 2020 shows a loss of 557 t.kr. deficit of 5 t.kr. last year, and the company's balance she per 31 December 2020 shows negative equi of 42 t.kr. The company has been hit hard b COVID in the financial year. The primary ra material for mushroom cultivation, coffee grounds from workplaces has been a scarc resource. Marketing mushrooms to restaurants has also been challenged. The company has adapted to the situation by selling to private individuals, as well as increased focus on online sales. With this transformation, the company has managed t grow compared to the previous year, but at higher costs than expected, which negativel affects the profit for the year.
				Number of Employees	4-12	5-9	
				Capital (kr)	424,157	406,250	
				Net sales	1,606,000	1,369,000	
				Cost of raw materials and consumables	-540,000	-464,000	
				Other external costs	-603,000	-403,000	
				Gross profit	463,000	502,000	
				Personnel costs	-827,000	-826,000	
				Depreciation and amortisation of intangibles and material fixed assets	-293,000	-312,000	
				Other operating costs	0	-70,000	
				Profit before financial items	-657,000	-706,000	
				Financial costs	-57,000	-28,000	
				Profit before tax	-714,000	-734,000	
				Tax on profit for the year	157,000	161,000	
				Profit for the year	-557,000	-573,000	
Beyond Mushrooms Aps		**The purpose of the company is to conduct activities in the trade and production of mushrooms and related activities.**	**SME**		**2020**	**2019**	The company's profit and loss account for 2020 shows a loss of 219,000 DKK against a deficit of DKK 221,000 DKK last year, and th company's balance sheet at 31 December 20 was 1.5% of the total. December 2020 show equity of 651,000 DKK During the year the
				Number of Employees	1	2	
				Capital	329,000	300,000	

				Net sales	2	0	company received a loss of 569,000 DKK fo project, which will be completed in 2021.
				Other operating income	569,000	682,000	
				Other external costs	-224,000	-259,000	
				Gross profit	347,000	423,000	
				Personnel costs	-415,000	-668,000	
				Depreciation and amortisation of intangibles and material fixed assets	-99,000	-36,000	
				Profit before financial items	-167,000	-281,000	
				Financial income	0	1,000	
				Financial costs	-5,000	-3,000	
				Profit before tax	-172,000	-283,000	
				Tax on profit for the year	-47,000	62,000	
				Profit for the year	-219,000	-221,000	
Funga Farm	**fungafarm .com**	**The purpose of the company is to produce fungus and, in cooperation with fungi, to promote health.**	**SME**		**2020 (kr)**	**2019 (kr)**	
				Number of Employees	2	2	No events have occurred after the end of th financial year which could significantly affe the financial position of the Company.
				Capital	66,700	16,000	
				Gross profit	196.572	-84.923	
				Personnel costs	-64.913	0	
				Profit before financial items	131.659	-84.923	
				Other financial costs	-165	0	
				Profit before tax	131.494	-84.923	
				Tax on profit for the year	-11.374	0	
				Profit for the year	120,120	-84.923	
Tvedemose Ejendom ApS	**tvedemos e.dk**	**Tvedemose produces and sells organic eggs, hens, fruit and juices. The organic manure from chicken production is used as an ingredient**	**SME**		**2019/20 (kr)**	**2018/19 (kr)**	The company is located on Lolland and is pa of the circular and sustainable production i Tvedemose near Lundby. The production is run by local employees. Sustainability and

		in compost, which is the foundation for mushroom production.					recycling are focal points for all production i Tvedemose and this is done in collaboratio with Tvedemose Food ApS and Tvedemose Ecology ApS. Orchard and stables are undergoing a majo renovation and thus stand more robust for future production. The result for the year sha be deemed not satisfactory. During the financial year, the parent company granted a grant of DKK 3 million, so that the own fund per share of the capital will be June 30, 2020 positive with DKK. 1,371,256. The grant is recognised in the financial statements as a transaction in equity and thus does not affec the profit for the year.
				Number of Employees	5-21	1-19	
				Capital	50,000	50,000	
				Gross Loss	-939.477	1.799.827	
				Personnel costs	-477.433	-1.576.716	
				Depreciation and amortization fixed assets	-328.922	-299.716	
				Operating profit	-1.745.832	-76.605	
				Financial income	35.157	15	
				Financial costs	-198.49	-277.413	
				Profit for the year before tax	-1.909.165	-354.003	
				Tax on profit for the year	498.701	85.723	
				Profit for the year	-1.410.464	-268.28	
Tvedemose Økologi ApS	**tvedemose.dk**	**Tvedemose Ecology ApS produces and sells organic mushrooms to supermarket chains, food service and online shops in Denmark.**	**SME**		**2020 (kr)**	**2019 (kr)**	
				Number of Employees	149-163	142-161	The result for 2019/2020 is satisfactory an meets budget expectations. The corona pandemic has not affected sales of mushroon State aid packages have been used nothing more than a shift in VAT payments. It cause the increase under other debt.
				Capital	50,000	50,000	
				Gross profit	31.366.970		
				Personnel costs	-25.562.490		
				Operating profit	5.804.480		
				Financial income	259		
				Financial costs	-220.741		
				Profit for the year before tax	5.583.998		
				Tax on profit for the year	-1.171.830		
				Profit for the year	4.412.168		

Bygaard ApS		The company's main activity is to operate store operations, fungal and micro-green production.	SME		2020 (kr)	2019 (kr)	On March 30, Denmark went into lockdown a a result of COVID19. This meant that the majority of the company's sales channels, th restaurants, shut down indefinitely. The far shop and micro-green production also close as a consequence of internal risk analysis fo the spread of infection. Already the followin week, a collaboration had been established with the company Fresh.Land, which supplie boxes of organic fruit and vegetables to the home addresses of home consumers, to purchase all of the company's products. In doing so, the company generated more tha 60,000 sales of mushrooms in April. The demand from Fresh.Land is far above ou current capacity. We therefore expect three- four-fold mushroom production during May be able to follow the increasing demand fro both existing and pending customers. The financing of the extension comes from a combination of advance payments on goods capital increase and small fund resources. I July-August, our first 40-foot mushroom-growing container was establish in front of our existing 20-foot growing container. Alongside the production, a 20-fo refrigerated container and a 40-foot storag container were placed.
				Number of Employees	1-3	1-3	
				Capital	42,666.66	10	
				Gross profit	-60.234	148.735	
				Personnel costs	-22.697	-39.583	
				Depreciation and amortisation of intangible and tangible fixed assets	-29.356	0	
				Profit before financial items	-112.287	109.152	
				Financial costs	-3.014	-2.796	
				Profit before tax	-115.301	106.356	
				Tax on profit for the year	7.968	-24.576	
				Profit for the year	-107.333	81.78	
				Profit coverage suggestions	0	39.9	
				Transferred to reserve for entrepreneurial companies	-107.333	41.88	
				Retained result	-107.333	81.78	
				Fixed turnover		40-50,000 DKK per month	
All data derived from virk.dk, a publicly accessible website listing all registered Danish company’s public financial information.							