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REVIEW

Zero waste management of spent mushroom compost

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Abstract

Edible mushroom are grown commercially using lignocellulosic waste by applying a biological process. However after the harvesting season about 70% of the substrate remain as a spent mushroom compost (SMC). SMC can be the source for retrieving value-added products which support zero waste approach. In this paper, the fate of SMC from agricultural production will be discussed focusing on its utilization. Based on the previous reports, major uses of SMC were in the agricultural field as mushroom media, animal feed, plant compost, fertilizer and others. Extended usage of SMC, i.e., for second cultivation is proposed in this review. In addition, the SMC was also applied in renewable energy production, e.g., feedstock for biogas, bioethanol or biohydrogen.

Keywords SMC · Agriculture use · Renewable energy · Zero waste management

Introduction

Mushroom industry has shown significant growth over the years contributed by the world's population increment. This was indicated by the consumption of mushroom per capita that improved tremendously from only 1 kg in 1997 to 4.7 kg in year 2013 [1]. Edible mushroom is the major harvest from the industry with over 34 million tones produced in 2013 [2]. Various agricultural waste such as cotton waste, rice straw, saw dust and oil palm empty fruit bunch (EFB) are used as the growth media [3]. With the reputation as health food and the changing trends diet of consumer, demands of mushroom are expected to increase in future.

Another significant issue related with the industry is the spent mushroom compost (SMC) produced from the post-harvest process. The SMC required proper management other than dumping or burning [4]. Furthermore, the rising concern on circular and sustainable economy recently had increase the interest for recycling the SMC [5]. For example in Malaysia, in overall about 69% of the SMC were dumped in the ground or landfill sites while 28% were recycles for agriculture use and the remaining 3% were incinerated [6]. The recycling of the SMC may differs in other countries but the reality is there rate is still low. Utilizing SMC as fertilizer, soil conditioner and for horticulture application had been reported by previous researcher [7–9].

SMC is also potentially used in renewable energy field either directly applied as fuel pellet or to be utilized as feedstock for biofuel [2, 10, 11]. In recent development, the potential of SMC in Anaerobic Digestion (AD) for biogas had also been investigated by few researcher [4, 12]. SMC is suitable substrate due to it already undergoing biological treatment process thus producing the similar compound [13]. Several literatures such as by Hanafi et al. [13] reviewed on application of SMC for fertilizer, animal feedstock and renewable energy while Kulshrestha [14] work discussed the potential of SMC as adsorbent

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for wastewater treatment. However, the literatures that explained the relation of SMC toward zero waste management are scarce. The recycling of SMC will adapt the zero waste policy in which targeting to minimize this waste. Many countries have yet to implement the policy in the mushroom industries although extensive use of SMC for various purposes had been reported in China [15].

In this review, the uses of SMC in agriculture field and for renewable energy production will be discussed. Furthermore SMC recycling for supporting the zero waste management policy will be highlighted.

The production of SMC

SMC are comprised of different types of agriculture waste, the residual nutrient and the leftover fungal mycelium [16]. Figure 1 shows an example of SMC from *Pleurotus* sp. and *Volvariella* sp. cultivation.

Depending on the species, the mushroom cultivation cycle take about 2–6 months. For example, *Volvariella volvacea* is grown and harvested within 2 months while *Pleurotus* season may last for 5 months [17, 18]. Moreover, the biological efficiency (B.E) of oyster mushroom is up to 150% while for straw mushroom is in the range of 30–40% [18, 19]. It is estimated the amount of SMC produced per kg of mushroom harvested was between 4 and 5 kg [20]. Table 1 depicted amount of mushroom produced in the world.

Fig. 1 **a** Spent mushroom compost block of *Pleurotus* sp. **b** Spent mushroom compost growth bed residual from *Volvariella volvacea* cultivation

Table 1 Production of mushroom based on countries and continent in 2013 [1]

Country/continent	Billion kg
China	30.4
European Union	1.1
America	1
Rest of Asia	1.3
Others	1

SMC composition

The fruiting body development is driven by the bioconversion of cellulosic component in the substrate catalyzed by the lignocellulolytic enzymes [21]. The characteristic of SMC varies greatly depending on composting processes, methods of cultivation and climate [22]. Table 2 shows the cellulose, hemicellulose and lignin composition in the SMC. Ratio of cellulose, hemicellulose and lignin in the SMC varies significantly based on the substrate types and sources of mushroom. Rate of degradation of these components mostly related with the lignocellulolytic enzymatic systems poses by the mushroom in which are different in the species. For example, *Volvariella volvacea* is reported lacking of ligninolytic enzymes while mushroom species like *P. sajor-caju* and *L. edodes* able to suit in high lignin substrate [19].

Recycling and utilizing SMC

In Malaysia, most of the mushroom farmer just burnt or dumped SMC into the ground or just spread it on the soil [32]. Some issues arised is how these activities might affect the environment. For instance, open burning is prohibited under section 29A (2) and 29(B), Environmental Quality Act, 1974 [33]. But there is an exemption for open burning of the plant with disease, in which the SMC is often regarded as contagious to other plants if dumped directly. Therefore, burning process in the farm can be legalized. Figure 2 shows the flow of management for SMC in the mushroom industry in Malaysia.

With the abundance of SMC, various applications have been explored to fully utilize the substrate. The strength, weakness and measures taken for each SMC application are summarized in Table 3.

Mushroom recultivation

The carbon, nitrogen, cellulose and lignin contents are low in the SMC compared to the fresh substrate due to fungal biodegradation during cultivation [24]. Prior to use as mushroom compost, SMC required pre-treatment steps including pasteurization, grinding and supplementation with nutrient. Formulating of SMC with carbon and nitrogen sources improved the mushroom compost quality [25]. Table 4 presented examples of SMC recycling for mushroom cultivation.

Biofertilizer and compost

Excessive use of chemical fertilizers has resulted in degradation of soil fertility, water hardness and contributed to environmental problems [56]. SMC is one of the options for conversion to biofertilizer. Amendment processes such as additional of organic nutrient or starter culture are required for SMC to be used as fertilizer. Triyono et al. [57] determine that compost made from SMC of EFB mixed with organic materials is complied to standard quality requirement. Uzun [22] points out that weathered SMC is suitable as fertilizer and soil conditioner better than fresh SMC and chicken manure. While Sendi et al. [58] reported that SMC at 50% in the growth media is suitable for growing kai-lan. Some detailed analysis of nutrient and trace element composition for different type SMC and commercial compost is presented in Table 5.

Table 2 Cellulose, hemicellulose and lignin content of different type of spent mushroom compost

Source of SMC (mushroom type)	Type of substrate	Compositional analysis (%)			References
		Cellulose	Hemicellulose	Lignin	
Lentinula sp.	Oak sawdust	30.6	4	19.4	[24]
Agaricus bisporus	Millet straw	19.44	9.03	37.67	[25]
Pleurotus ostreatus	Barley straw + nitrogen source	28.32	17.52	7.12	[26]
Auricularia	Beech-wood dust	13	16	19	[27]
Flammulina sp.	Cotton seed hulls	23.77	17.54	16.32	[28]
Volvariella volvacea	Oil palm EFB	20.90	11.64	11.58	[23]
Pleurotus eryngii	Saw dust + sweet potatoes	34.7	7.1	14.8	[29]
Agaricus bisporus	Straw + peat	38	19	25	[30]
Agaricus bisporus	Wheat straw	7.1	4.5	24.6	[31]
Pleurotus ostreatus	Wheat straw	30.5	17.8	19.4	[31]

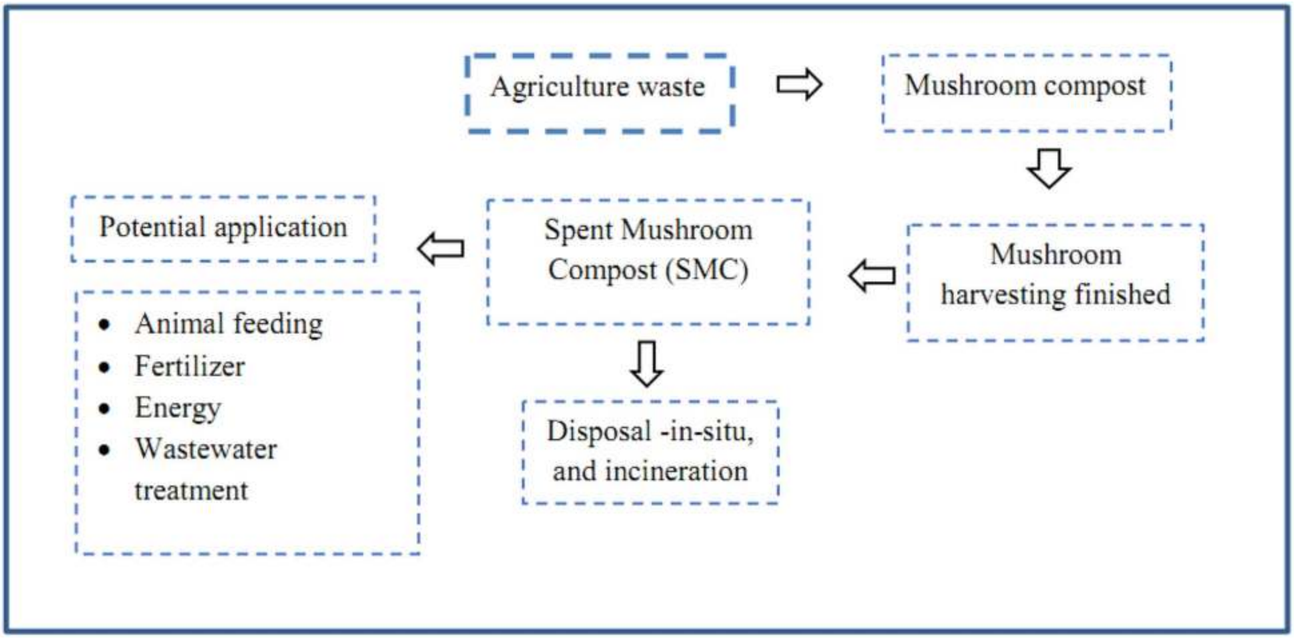

Fig. 2 Flow of spent mushroom compost management in the mushroom industry [34]

Animal feed

In vitro digestion method is used to study potential SMC as animal feed [59]. The crude protein digestibility is increased up to 70%. While another study shows that SMC of wheat straw from *Agaricus bisporus* mushroom can be used as ruminant feed that improve the nutrient intake, digestibility and nitrogen balance [60, 61]. Moreover, the SMC is also applied as an animal feed in poultry industry. Chang et al. [62] found that 5% SMC supplementation in meal improve the growth rate and meat sensory attributes of grower geese.

Soil treatment and plant substrate

SMC is a water retaining and good ventilating material with high biodegradability [15]. The use of *Pleurotus eous* SMC at 10% as soil conditioner for capsicum and tomato seedlings increase the plant height [63]. Oei [15] points out the application of SMC of straw and cotton seed hull also improving soil quality. While Zhang et al. [64] conducted a research on SMC of *Flammulina velutipes* for tomato and cucumber seedlings which shows the unamend SMC has higher bulk density and suitable properties as growing media. While Marques et al. [65] find that substrate with 45% *Agaricus subrufescens* SMC for lettuce seedling is suitable for the growth. Lopes et al. [66] also reported the positive result using similar type of SMC for growing tomato.

Biogas

The compositional quality of the substrate as feedstock for biogas generation is important and could effect the process [46]. Different types of SMC may produce variable results due to different pre-treatment and anaerobic digestion period [47, 67]. Mamimin et al. have demonstrated the application of SMC of EFB from *Volvariella volvacea* cultivation that yielded about 281 L CH_4/kg VS [68]. Nuchdang et al. [69] report a promising result using of paragrass treated with *C. cinereal* and *P. tricholoma* (BCC2285) that produced 311 L CH_4/kg VS. While methane produced from SMC of rice straw cultivated with *P. ostreatus* is 263 L/kg VS [4]. These data are comparable to the common substrate such as food waste (280.9 L/kg VS) and pig manure (253.8 L/kg VS) [4]. Meanwhile the digestate may usually cause mechanical troubles such as clogging of pipes that can be minimized using suitable pumping and piping system. The digested liquid also can be potentially use as fertilizer.

Biohydrogen

The hydrogen productivity obtained from SMC can be improved through acid hydrolysis which demonstrates the practical value of SMC [70]. In addition, with medium optimization, non-sterile fermentation and acid pre-treatment, the use of SMC can be economical. *Clostridium* sp. is a versatile species that can degrade lignocellulosic materials to produce acetate, hydrogen, lactate and ethanol. The bacteria able to express cellulolytic enzymes with the help

Table 3 Strength, weakness and measures to overcome of SMC application

SMC application	Strength	Weakness	Measures to overcome	References
Mushroom recultivation	Cost reduction-onsite management of waste Extending production of mushroom	Yield efficiency is less Tendency of contamination by other species	Option as a co-substrate Option for cultivation of different species	[35–37]
Biofertilizer and compost	Good bulking agent Faster time for maturing process Better nutrient composition	Commercialization of technology is still low	Promotion and encouragement to the industry player for technology application	[38]
Animal feed	Good substitute Comparable to commercial in terms of nutrient content	Incubation time/pre-treatment longer (after season end) substrate, 8–12 weeks compared to commercial-only 4 weeks Costly operation—maintaining sterile condition	Improving composting process, additional of compound to enhance enzymatic degradation	[39]
Soil treatment, plant substrate and biochar	Cost effective and easy management. Efficiently improve soil quality and nutrient for plant	Direct use may lead to contagious plant disease and fungal infection	Pre-treatment required prior use for better effect	[40]
Biogas	Good substrate and lignin content reduced Direct use Better yield compared to other lignocellulose waste	Research and development ongoing. Factors for optimization in research	Ongoing work and industry–academic partnership to materialize commercialization	[41]
Biohydrogen	Better yield and faster fermentation time from other lignocellulose substrate	Required pre-treatment. Research is ongoing. Small-scale level, pilot scale data are scarce	Research work still ongoing	[42, 43]
Bioethanol/biobutanol	Easy management of waste. Better than raw lignocellulose materials	Required pre-treatment for better yield and high cost. Research is ongoing, pilot scale data are scarce	Research is currently ongoing	[44, 45]
Biocrude/biooil	High availability substrate. Good potential	High moisture, ash concentration and presents inorganic hindrance to the process	Improve the conversion process, i.e., hydrothermal Liquefaction, Fast pyrolysis and Torrefaction	[46, 47]
Fuel pellet briquettes	High availability, easy management of waste	Low calorific value, high moisture—required drying	Added as mixture in briquette or used as moderate quality briquette	[12, 48]

Table 4 The utilization of the spent mushroom compost as a media substrate for different mushrooms cultivation

Mushroom species recultivation	Source of SMC	Additional media composition	Yield efficiency/advantages/remarks	References
Agarocybe chaxingu	*Pleurotus eryngii*	10–20% *Tenebrio molitor* feces/wheat bran	Increase biological efficiency	[49]
Pleurotus sajor-caju	*Shiitake*	12% soy bean: 1% $CaCO_3$	Produce 79% biological efficiency	[50]
Agaricus blazei	*Pleurotus* spp.	50% sunflower seed hull	Similar yield to composted substrate	[51]
Agaricus bisporus	*ND*	Non-compost substrate	Low contamination rate	[52]
Pleurotus ostreatus	*Agaricus* sp.	Mix straw 50%	Achieving 48.9% biological efficiency	[53]
Volvariella volvacea	*Agaricus bisporus*	ND	ND	[54]
Pleurotus ostreatus, Agrocybe cylindracea and *Hericium erinaceus*	*Agaricus brasiliensis*	ND	Shorten composting period	[5, 55]
Agrocybe cylindracea	*Pleurotus* sp.	ND	150% better than rubber sawdust substrate	[35]

ND not determined

Table 5 Detailed analysis of some spent mushroom compost and commercial compost

Content	SMC *A. sub*[a]	SMC *A. bisp.*[a]	SMC *P. caju*[b]	SMC 8–16 months[c]	Green waste compost[a]	Peat substrate[a]	Vermicompost[a]
Na mg L^{-1}	1200	1300	ND	220	40	32	600
K mg L^{-1}	4900	5500	5300	1030	600	182	1000
Cl mg L^{-1}	2400	2400	ND	ND	30	11	700
B mg L^{-1}	0.88	0.69	ND	ND	1.5	0.2	1.6
Mg mg L^{-1}	360	330	1500	910	125	125	350
S mg L^{-1}	1200	1600	ND	ND	50	52	200
Ca mg L^{-1}	2000	2500	5100	616	900	971	2000
Mn mg L^{-1}	6.6	2.7	ND	438.62	2	2.4	2.5
Fe mg L^{-1}	29	6.6	ND	92	1	1.5	0.4
P mg L^{-1}	110	100	1600	0.55	120	40	150
NH_4–N mg L^{-1}	5	3	ND	ND	5	50	1
NO_3–N mg L^{-1}	5	290	ND	ND	30	74	650
TN mg kg^{-1} FW	4530	5330	3400	1920	2000	3000	6000
Dry matter	25%	30%	ND	24%	42%	ND	45%
Ash content	64%	62%	ND	ND	60%	ND	40%
pH	5.1	8.7	6.1	8.05	7	5.8	7.7
EC (mS cm^{-1})	2.6	23	1.331	ND	2	1.3	9

ND not determined

[a]60, [b]59, [c]22

of a complex structure on the surface of the cell are called as cellulosome [71]. Lin et al. [72] study on the effects of surfactants (PEG8000 and JFCE) on SMC fermentation using *Clostridium thermocellum*. As a result, a washing process is required for SMC and optimization of the fermentation medium is suggested for efficient yield. Another study by Lin et al. [73] apply the indigenous bacteria as inoculum and using SMC in which yielded hydrogen production rate (6.84 mmol H_2/L-day).

Bioethanol/biobutanol

Bioethanol has attracted attention as renewable fuel due to limitation in fossil fuels and the production of greenhouse gases from these fuels [74]. Non-edible biomass such as lignocellulosic materials is better option for bioethanol production [75, 76]. Ryden et al. [44] suggest the SMC of sorghum chaff is suitable for second-generation bioethanol. The yield of bioethanol could be further improved by pre-treatment strategies such as acid, microbes and steam explosion for the delignification of cellulose materials [76–78]. Tinggang Li et al. [79] isolated from SMC species namely *Thermoanaerobacterium thermosaccharolyticum* TG57 that is capable of converting cellulose, a plant-based material, to biobutanol.

Volvariella volvacea cultivation model for zero waste management

The zero waste concept aims to divert waste from landfills by applying 3R rules which are Reduce, Reuse and Recycle or elimination of waste [80]. Basically, 3R are the first waste hierarchy introduced in waste management systems which has been expanded to 9R framework. This 9R framework consists of strategies and policies to support zero waste system and in line with circular economy requirement. Figure 3 shows the new zero waste hierarchy in waste management.

In the context of this article, SMC is proposed as sustainable feedstock. Figure 4 portrays a zero waste management of *Volvariella volvacea* cultivation. *Volvariella volvacea* is a lowland mushroom that grows in the hot climate using plethora of agriculture waste. Although this mushroom has a long history of cultivation, the low B.E remained to be unsolved [83]. Meanwhile the use of oil palm waste especially EFB for *Volvariella volvacea* cultivation is regaining attention by the farmers particularly in Indonesia and Malaysia due to the abundance of this substrate. It is suggested for improving the B.E of *Volvariella volvacea* cultivation using EFB, the SMC should be recycled for second cultivation. Whereby it is expected that the B.E will increased up to 40–50% in total. Then the final SMC can be utilized for agriculture and energy production as depicted in the model to achieve zero waste policy.

Conclusion

SMC offers a full potential for recycling into beneficial product and provide opportunities for creating new income for the growers and communities. Future study should proposed

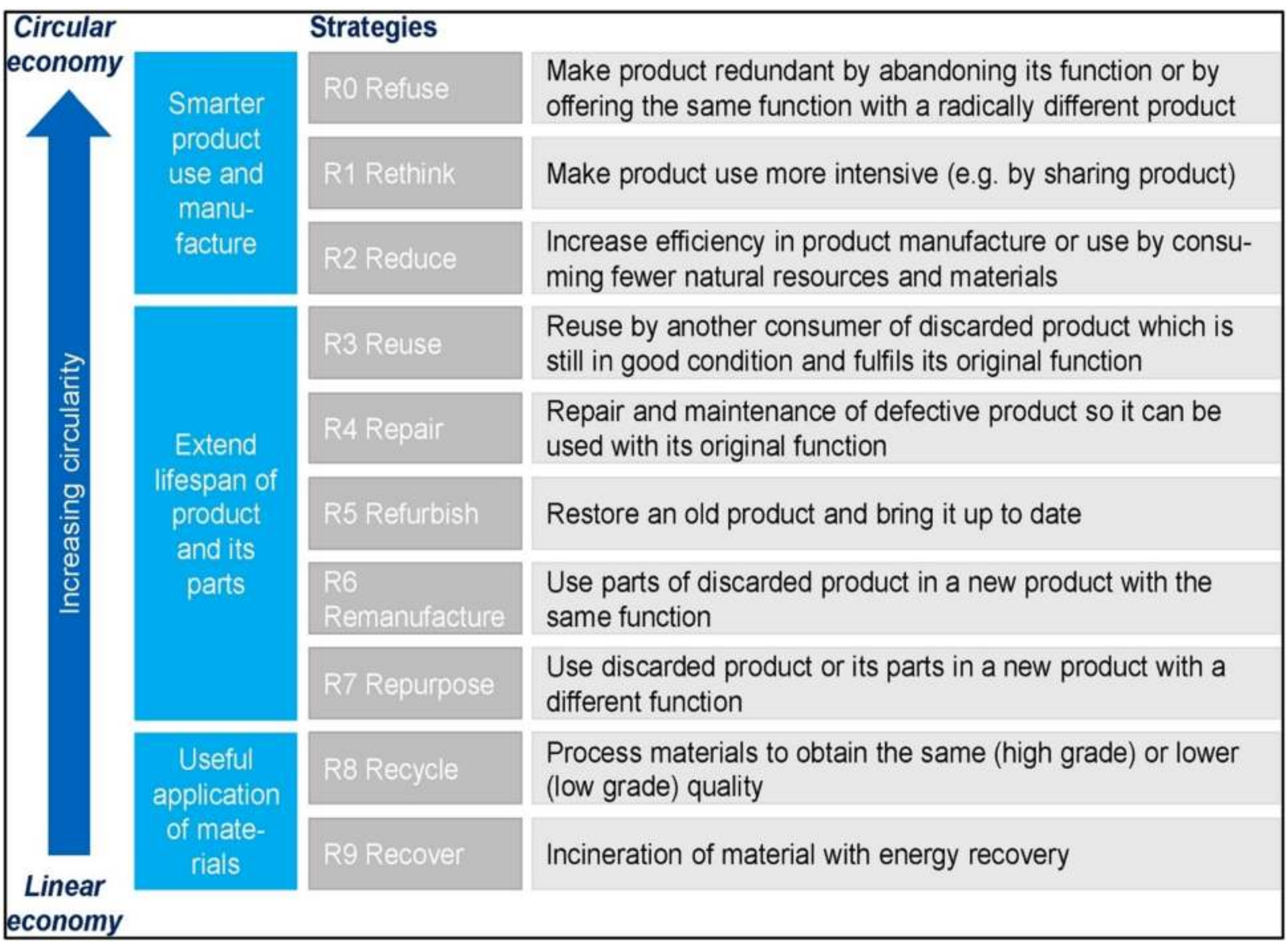

Fig. 3 9R framework of zero waste hierarchy [81, 82]

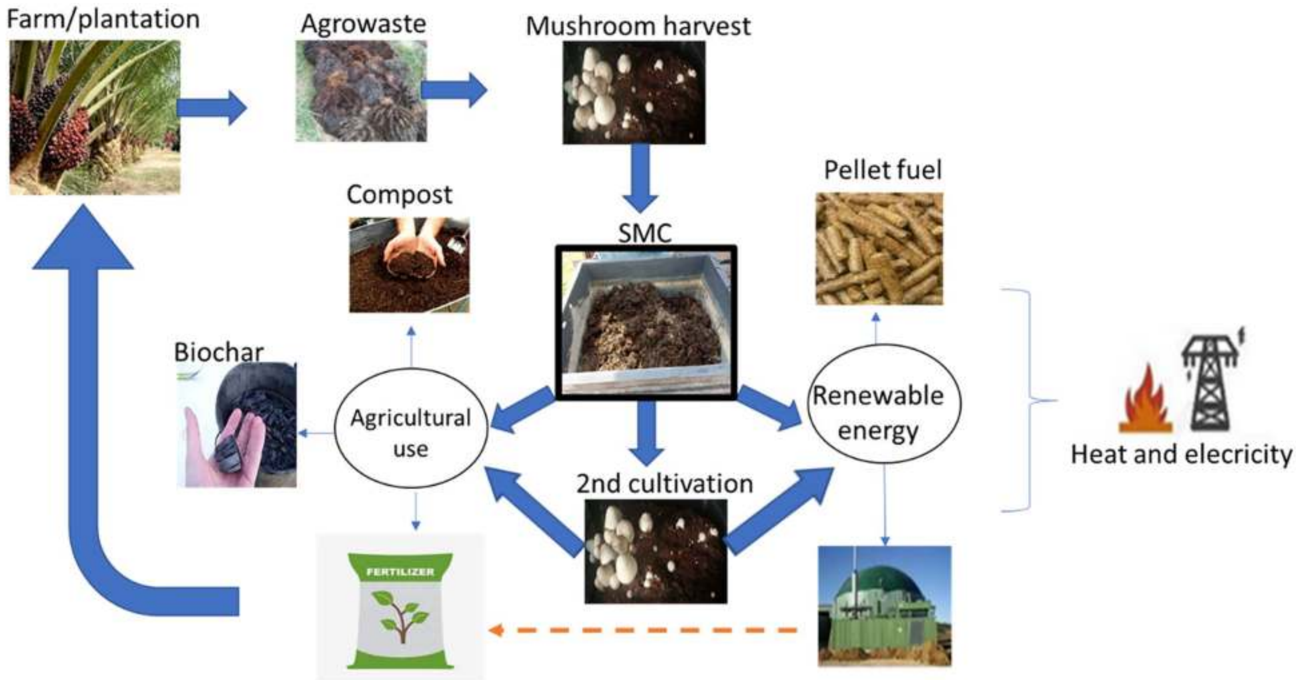

Fig. 4 Zero waste management model *Volvariella volvacea* cultivation using oil palm waste

on the technological advancement in the SMC conversion to product and economic feasibility study on the product. In near future, integration between palm oil industry with mushroom industry is expected to be materialized and setting a benchmark for zero waste management and circular economy.

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References

1. Royse DJ, Baars J, Tan Q (2017) Current overview of mushroom production the world. In: Zied DC, Pardo-Giminez A (eds) Edible and medicinal mushrooms: technology and applications. JohnWiley & Sons Ltd, Hoboken, pp 5–13
2. Grimm D, Wösten HAB (2018) Mushroom cultivation in the circular economy. Appl Microbiol Biotechnol 102(18):7795–7803. https://doi.org/10.1007/s00253-018-9226-8
3. Oseni TO, Dlamini SO, Earnshaw DM, Masarirambi MT (2012) Effect of substrate pre-treatment methods on oyster mushroom (*Pleurotus ostreatus*) production. Int J Agric Biol 14(2):251–255
4. Pérez-Chávez AM, Mayer L, Albertó E (2019) Mushroom cultivation and biogas production: a sustainable reuse of organic resources. Energy Sustain Dev 50:50–60. https://doi.org/10.1016/j.esd.2019.03.002
5. Jasińska A (2018) Spent mushroom compost (SMC)–retrieved added value product closing loop in agricultural production. Acta Agrar Debr. https://doi.org/10.34101/actaagrar/150/1715
6. Singh AD, Vikineswary S, Abdullah N, Sekaran M (2011) Enzymes from spent mushroom substrate of *Pleurotus sajor-caju* for the decolourisation and detoxification of textile dyes. World J Microbiol Biotechnol 27(3):535–545. https://doi.org/10.1007/s11274-010-0487-3
7. Jasińska A, Wojciechowska E, Stoknes K, Krajewska K (2016) Combined cultivation of edible mushrooms and vegetables. In: Book of proceedings 7th international scientific agriculture symposium, Agrosym 2016, pp 200–206
8. Curtis J, Suess A (2006) Report: value-added strategies for spent mushroom substrate in BC. British Columbia Ministry of Agricultural and Lands, British Columbia
9. Das M, Uppal HS, Singh R, Beri S, Mohan KS, Gupta VC, Adholeya A (2011) Co-composting of physic nut (*Jatropha curcas*) deoiled cake with rice straw and different animal dung. Bioresour Technol 102:6541–6546
10. Najafi B, Ardabili SF (2018) Application of ANFIS, ANN, and logistic methods in estimating biogas production from spent mushroom compost (SMC). Resour Conserv Recycl 133:169–178. https://doi.org/10.1016/j.resconrec.2018.02.025
11. Purnomo A, Suprihatin S, Romli M, Hasanudin U (2018) Biogas production from oil palm empty fruit bunches of post mushroom cultivation media. IOP Conf Ser Earth Environ Sci. https://doi.org/10.1088/1755-1315/141/1/012024
12. Ryu C, Finney K, Sharifi VN, Swithenbank J (2008) Pelletised fuel production from coal tailings and spent mushroom compost—part I. Identification of pelletisation parameters. Fuel Process Technol 89(3):269–275. https://doi.org/10.1016/j.fuproc.2007.11.035
13. Hanafi FHM, Rezania S, Taib SM, Din MFMd, Yamauchi M, Sakamoto M, Ebrahimi SS (2018) Environmentally sustainable applications of agro-based spent mushroom substrate (SMC): an overview. J Mater Cycles Waste Manage 20(3):1383–1396. https://doi.org/10.1007/s10163-018-0739-0

14. Kulshreshtha S (2019) Removal of pollutants using spent mushrooms substrates. Environ Chem Lett 17:833–847. https://doi.org/10.1007/s10311-018-00840-2
15. Oei P, Hui Z, Jianhua L, Meiyuan C, Yi C (2008) The alternative uses of spent mushroom compost. In: Proceeding of the sixth international conference on mushroom biology and mushroom products, Germany, pp 231–245
16. Jordan SN, Mullen GJ, Murphy MC (2008) Composition variability of spent mushroom compost in Ireland. Bioresour Technol 99:411–418
17. Azhar M, Yuzaidi M, Hafizah SN (2018) Teknologi penanaman cendawan volvariella. Penerbit Agensi Nuklear, Malaysia, pp 5–15
18. Ali N, Tabi ANM, Zakil FA, Fauzai WNFM, Hassan O (2013) Yield performance and biological efficiency of empty fruit bunch (EFB) and palm pressed fibre (PPF) as substrates for the cultivation of *Pleurotus ostreatus*. J Teknol. https://doi.org/10.1113/jt.v64.1243
19. Chang ST (1978) *Volvariella volvacea*. In: Chang ST, Hayes WA (eds) The biology and cultivation of edible mushrooms, 1st edn. Elsevier, USA, pp 573–603. https://doi.org/10.1016/b978-0-12-168050-3.50033-5
20. Williams BC, McMullan JT, McCahey S (2001) An initial assessment of spent mushroom compost as a potential energy feedstock. Bioresour Technol 79(3):227–230
21. Sun X, Zhang R, Zhang Y (2004) Production of lignocellulolytic enzymes by *Trametes gallica* and detection of polysaccharide hydrolase and laccase activities in polyacrylamide gels. J Basic Microbiol 44:220–231
22. Uzun I (2004) Use of SMC in sustainable fruit production. J Fruit Ornam Plant Res 12(Special edition):157–165
23. Triyono S, Haryanto A, Telaumbanua M, Dermiyati D, Lumbanraja J, To F (2019) Cultivation of straw mushroom (*Volvariella volvacea*) on oil palm empty fruit bunch growth medium. Int J Recycl Org Waste Agric. https://doi.org/10.1007/s40093-019-0259-5
24. Atila F (2019) Compositional changes in lignocellulosic content of some agro-wastes during the production cycle of shiitake mushroom. Sci Hortic 245:263–268. https://doi.org/10.1016/j.scienta.10.029
25. Zhang HL, Wei JK, Wang QH, Yang R, Gao XJ, Sang YX, Chen QJ (2019) Lignocellulose utilization and bacterial communities of millet straw based mushroom (*Agaricus bisporus*) production. Sci Rep 9(1):1–13. https://doi.org/10.1038/s41598-018-37681-6
26. Nasreen Z, Ali S, Usman S, Nazir S, Yasmeen A (2016) Comparative study on the growth and yield of *Pleurotus Ostreatus* mushroom on lignocellulosic by-products. Int J Adv Res Bot 2(1):42–49. https://doi.org/10.20431/2455-4316.0201006
27. Liers TA, Ullrich R, Hofrichter M (2011) Patterns of lignin degradation and oxidative enzyme secretion by different wood and litter colonizing basidiomycetes and ascomycetes grown on beech-wood. FEMS Microbiol Ecol 78(1):91–102. https://doi.org/10.1111/j.1574-6941.2011.01144.x
28. Xie C, Gong W, Yan L, Zhu Z, Hu Z, Peng Y (2017) Biodegradation of ramie stalk by *Flammulina velutipes*: mushroom production and substrate utilization. AMB Express. https://doi.org/10.1186/s13568-017-0480-4
29. Lou Z, Sun Y, Zhou X, Baig SA, Hu B, Xu X (2017) Composition variability of spent mushroom substrates during continuous cultivation, composting process and their effects on mineral nitrogen transformation in soil. Geoderma 307:30–37. https://doi.org/10.1016/j.geoderma.2017.07.033
30. Syguła E, Koziel JA, Białowiec A (2019) Proof-of-the-concept of spent mushrooms compost torrefaction—preliminary studies of process kinetics and the influence of temperature and duration on calorific value of the biochar. https://www.Preprints.org. Accessed 5 May 2020
31. Fang W, Zhang X, Zhang P, Morera XC, van Lier JB, Spanjers H (2019) Evaluation of white rot fungi pretreatment of mushroom residues for volatile fatty acid production by anaerobic fermentation: feedstock applicability and fungal function. Bioresour Technol 297:122447
32. Zainol RM, Nazri M, Tamami M, Aznie R, Rose C, Mapjabil J, Marzuki M (2018) Kaedah pengurusan sisa substrat cendawan dalam kalangan Agropreneur Muda Cendawan. Geografi 6(3):67–75
33. http://www.doe.gov.my/. Accessed 11 May 2020
34. Phan CW, Sabaratnam V (2012) Potential uses of SMC and its associated lignocellulosic enzymes. Appl Microbiol Biotechnol 96(4):863–873
35. Noonsong V, Puttakun V, Tinsirisuk M, Seephueak P (2016) Recycling of spent *Pleurotus* compost for production of the *Agrocybe cylindracea*. Mycosphere. https://doi.org/10.5943/mycosphere/7/1/4
36. Ahlawat OP, Sagar MP (2007) Management of spent mushroom substrate. Technical bulletin. National Research Centre for Mushroom
37. Ashrafi R, Hian MH, Rahman MM, Jahiruddin M (2017) Reuse of spent mushroom substrate as casing material for the production of milky white mushroom. J Bangladesh Agric Univ 15(2):239–247
38. Li S, Li D, Li J, Li Y, Li G, Zang B, Li Y (2018) Effect of spent mushroom substrate as a bulking agent on gaseous emissions and compost quality during pig manure composting. Environ Sci Pollut Res 25(13):12398–12406. https://doi.org/10.1007/s11356-018-1450-3
39. Van Kuijk SJA, Sonnenberg ASM, Baars JJP, Hendriks WH, Cone JW (2015) Fungal treatment of lignocellulosic biomass: Importance of fungal species, colonization and time on chemical composition and in vitro rumen degradability. Anim Feed Sci Technol 209:40–50. https://doi.org/10.1016/j.anifeedsci.2015.07.026
40. Chang KL, Chen XM, Sun J, Liu JY, Sun SY, Yang ZY, Wang Y (2017) Spent mushroom substrate biochar as a potential amendment in pig manure and rice straw composting processes. Environ Technol 38(13–14):1765–1769. https://doi.org/10.1080/09593330.2016.1234000
41. Najafi B, Ardabili SF, Shamshirband S, Chau K-W (2019) Spent mushroom compost (SMC) as a source for biogas production in Iran. Eng Appl Comput Fluid Mech 13(1):967–982. https://doi.org/10.1080/19942060.2019.1658644
42. Lin HN, Wang YT, Zhu MJ (2017) Evaluation of spent mushroom compost as a lignocellulosic substrate for hydrogen production by *Clostridium thermocellum*. Int J Hydrogen Energy 42(43):26687–26694. https://doi.org/10.1016/j.ijhydene.2017.09.040
43. Hu BB, Zhu MJ (2017) Enhanced hydrogen production and biological saccharification from spent mushroom compost by *Clostridium thermocellum* 27405 supplemented with recombinant B-glucosidases. Int J Hydrogen Energy 42(12):7866–7874. https://doi.org/10.1016/j.ijhydene.2017.01.031
44. Ryden P, Efthymiou MN, Tindyebwa TAM, Elliston A, Wilson DR, Waldron KW, Malakar PK (2017) Bioethanol production from spent mushroom compost derived from chaff of millet and sorghum. Biotechnol Biofuels 10(1):1–11. https://doi.org/10.1186/s13068-017-0880-
45. Teoh TC, Soo CS, Heidelberg T, Zainudin A (2014) Bioethanol from spent mushroom sawdust waste by perchloric acid: easy sugars separation and hydrolysis without charring. Chiang Mai J Sci 41(3):513–523
46. Garrido R, Ruiz-Felix MN, Satrio JA (2012) Effects of hydrolysis and torrefaction on pyrolysis product distribution of spent mushroom compost (SMC). Int J Environ Pollut Remediat. https://doi.org/10.1159/ijepr.2012.014
47. Jasiūnas L, Pedersen TH, Toor SS, Rosendahl LA (2017) Biocrude production via supercritical hydrothermal co-liquefaction of spent

mushroom compost and aspen wood sawdust. Renew Energy 111:392–398. https://doi.org/10.1016/j.renene.2017.04.019
48. de Almeida Moreira BR, da Silva Viana R, Magalhães AC, Caraschi JC, Zied DC, Dias ES, Rinker DL (2020) Production of *Pleurotus ostreatus* var. Florida on briquettes and recycling its spent substrate as briquettes for fuel grade biosolids. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.1239
49. Zeng X-l, Han F, Ye J-l, Zhong Y-m (2017) Recycling spent *Pleurotus eryngii* substrate supplemented with *Tenebrio molitor* feces for cultivation of *Agrocybe chaxingu*. Int J Recycl Org Waste Agric 6:275–280. https://doi.org/10.1007/s40093-017-0171-9
50. Royse DJ (1993) Recycling of spent shiitake substrate for production of the oyster mushroom (*Pleurotus sajor-caju*). Mushroom News 41(2):14–18
51. Matute R, González D, Figlas CN (2011) *Agaricus blazei* production on noncomposted substrates based on sunflower seed hulls and spent oyster mushroom substrate. World J Microbiol Biotechnol 27(6):1331–1339
52. Mamiro DP, Royse DJ, Beelman RB (2007) Yield, size, and mushroom solids content of *Agaricus bisporus* produced on non-composted substrate and spent mushroom compost. World J Microbiol Biotechnol 23(9):1289–1296
53. Pardo-Giménez A, Buendía MRP, de Juan Valero JA, Pardo-González JE, Zied DC (2012) Cultivation of *Pleurotus ostreatus* using supplemented spent oyster mushroom substrate. Acta Hortic 933:267–272
54. Oei P (1991) Manual on mushroom cultivation: techniques species and opportunities for commercial application in developing countries. TOOL Publications, Amsterdam, p 274
55. Poppe J (2000) Use of the agricultural waste materials in the cultivation of mushrooms. Mushroom Sci 15:3–23
56. Savci S (2012) An agricultural pollutant: chemical fertilizer. Int J Environ Sci Dev 3(1):73–80. https://doi.org/10.7763/ijesd.2012.v3.191
57. Triyono S, Pujiono R, Zulkarnain I, Ridwan R, Haryanto A, Dermiyati D, Jamalam L (2019) The effects of empty fruit bunch treatments for straw mushroom substrate on physicochemical properties of a biofertilizer. Tek Pertan Lampung 8(2):120–129
58. Sendi H, Mohamed MTM, Anwar MP, Saud HM (2013) Spent mushroom waste as a media replacement for Peat Moss in Kai-Lan (*Brassica oleracea* var. Alboglabra) production. Sci World J. https://doi.org/10.1155/2013/258562
59. Zhang CK, Gong F, Li DS (1995) A note on the utilisation of SMCs in animal feeds. Biol Conserv 4(4):89–91. https://doi.org/10.1016/0006-3207(72)90131-0
60. Fazaeli H, Masoodi ART (2006) Spent wheat straw compost of *Agaricus bisporus* mushroom as ruminant feed. Asian Australas J Anim Sci 19(6):845–851. https://doi.org/10.5713/ajas.2006.845
61. Fazaeli H, Shafyee-Varzeneh H, Farahpoor A, Moayyer A (2014) Recycling of mushroom compost wheat straw in the diet of feedlot calves with two physical forms. Int J Recycl Org Waste Agric. https://doi.org/10.1007/s40093-014-0065-z
62. Chang SC, Lin MJ, Chao YP, Chiang CJ, Jea YS, Lee TT (2016) Effects of SMC meal on growth performance and meat characteristics of grower geese. Rev Bras Zootec 45(6):281–287. https://doi.org/10.1590/S1806-92902016000600001
63. Wiafe-Kwagyan M, Odamtten GT (2018) Use of *Pleurotus ostreotus* strain P-31 SMC (SMC) as soil conditioner on the growth and yield performance of *Capsicum annuum* L. and *Solanum lycopersicon* L. seedlings under greenhouse conditions in Ghana. Trop Life Sci Res 29(1):173–194
64. Zhang RH, Duan ZQ, Li ZG (2012) Use of SMC as growing media for tomato and cucumber seedlings. Pedosphere 22(3):333–342. https://doi.org/10.1016/S1002-0160(12)60020-4
65. Marques ELS, Martos ET, Souza RJ, Silva R, Zied DC, Dias ES (2014) SMC as a substrate for the production of lettuce seedlings. J Agric Sci 6(7):138–143. https://doi.org/10.5539/jas.v6n7p138
66. Lopes RX, Zied DC, Martos ET, de Souza RJ, da Silva R, Dias ES (2015) Application of spent *Agaricus subrufescens* compost in integrated production of seedlings and plants of tomato. Int J Recycl Org Waste Agric 4(3):211–218. https://doi.org/10.1007/s40093-015-0101-7
67. Horan H, Yaser AZ, Wid N (2000) Anaerobic digestion processes—applications and effluent treatment. Springer, Singapore (**ISBN 978-981-10-8128-6**)
68. Mamimin C, Chanthong S, Leamdum C, Thong SO, Prasertsan P (2021) Improvement of empty palm fruit bunches biodegradability and biogas production by integrating the straw mushroom cultivation as a pretreatment in the solid-state anaerobic digestion. Bioresour Technol 319:124227. https://doi.org/10.1016/j.biortech.2020.124227
69. Nuchdang S, Vatanyoopaisarn S, Phalakornkule C (2015) Effectiveness of fungal treatment by *Coprinopsis cinerea* and *Polyporus tricholoma* on degradation and methane yields of lignocellulosic grass. Int Biodeterior Biodegrad 104:38–45. https://doi.org/10.1016/j.ibiod.2015.05.015
70. Li YC, Wu SY, Chu CY, Huang HC (2011) Hydrogen production from mushroom farm waste with a two-step acid hydrolysis process. Int J Hydrogen Energy 36(21):14245–14251
71. Cheng J, Yu Y, Zhu M (2014) Enhanced biodegradation of sugarcane bagasse by *Clostridium thermocellum* with surfactant addition. Green Chem 16(5):2689–2695
72. Lin HN, Hu BB, Zhu MJ (2016) Enhanced hydrogen production and sugar accumulation from spent mushroom compost by *Clostridium thermocellum* supplemented with PEG8000 and JFC-E. Int J Hydrogen Energy 41(4):2383–2390
73. Lin CY, Lay CH, Sung IY, Sen B, Chen CC (2017) Anaerobic hydrogen production from unhydrolyzed mushroom farm waste by indigenous microbiota. J Biosci Bioeng 124(4):425–429. https://doi.org/10.1016/j.jbiosc.2017.05.001
74. Huzir NM, Aziz MMA, Ismail SB, Abdullah B, Mahmood NAN, Umor NA, Muhammad SAFS (2018) Agro-industrial waste to biobutanol production: eco-friendly biofuels for next generation. Renew Sustain Energy Rev 94:476–485. https://doi.org/10.1016/j.rser.2018.06.036
75. Shanavas S, Padmaja G, Moorthy SN, Sajeev MS, Sheriff JT (2011) Process optimization for bioethanol production from cassava starch using novel eco-friendly enzymes. Biomass Bioenerg 35(2011):901–909
76. Liao W, Liu Y, Liu C, Wen Z, Chen S (2006) Acid hydrolysis of fibers from dairy manure. Bioresour Technol 97(14):1687–1695. https://doi.org/10.1016/j.biortech.2005.07.028
77. McIntosh S, Vancov T (2010) Enhanced enzyme saccharification of Sorghum bicolor straw using dilute alkali pretreatment. Bioresour Technol 101(17):6718–6727. https://doi.org/10.1016/j.biortech.2010.03.116
78. Shi J, Chinn M, Sharmashivappa R (2008) Microbial pretreatment of cotton stalks by solid state cultivation of *Phanerochaete chrysosporium*. Bioresour Technol 99(14):6556–6564. https://doi.org/10.1016/j.biortech.2007.11.069
79. Li T, Zhang C, Yang K-L, He J (2018) Unique genetic cassettes in a *Thermoanaerobacterium* contribute to simultaneous conversion of cellulose and monosugars into butanol. Sci Adv 4(3):1701475. https://doi.org/10.1126/sciadv.1701475
80. Rajak SJ, Kim BS (2020) A holistic zero waste biorefinery approach for macroalgal biomass utilization: a review. Sci Total Environ 716:137067. https://doi.org/10.1016/j.scitotenv.2020.137067

81. Kirchherr DR, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
82. Potting M, Hekkert EW, Hanemaaijer A (2017) Circular economy: measuring innovation in the product chain—policy report. PBL Netherlands Assessment Agency
83. Umor NA, Abdullah S, Mohamad A, Ismail S, Ismail SI, Misran A (2020) Challenges and current state-of-art of the *Volvariella volvacea* cultivation using agriculture waste: a brief review. In: Yaser AZ (ed) Advance of waste processing technology. Springer Nature, Singapore, pp 145–156