

Organic Matter Decomposition: A View on The Fate of Lignocellulosic Materials

Susinjan Bhattacharya

School of Agriculture and Allied Sciences,
The Neotia University, Sarisa, West Bengal, India

ABSTRACT

Organic matter decomposition, a complex process with all the physico-chemical and biological factors leads to breakdown of organic residues. The prime role in this process is played by microorganisms with their enzymes. The process is beneficial not only to generate matters of soil fertility enhancement, but also it can lead to the products that can add value to soil. Slow and difficult matters to be decomposed like lingo-cellulosic materials can also be subjected to this decomposition process for the generation of not only new and beneficial microflora, but also products of value. The present work discusses here in brief the process of organic matter decomposition and its importance in rice straw breakdown and lignocellulosic material decomposition.

Keywords: Decomposition, Factors in decomposition, Microorganisms, Enzymes, Lignocellulose

INTRODUCTION

Decomposition as a complex process involves physico-chemical and biological factors to breakdown the raw materials to a usable simpler form of substance and usable as a soil amendment called as manure. There are two ways for the process of decomposition: aerobic (in presence of oxygen) and anaerobic (in absence of oxygen). Microorganisms play a bigger role in decomposition. [Texas A&M Agrilife Extension, 2023; UtahState University, 2023]. The common subjects for decomposition are waste matters. With regard to the ability of the substrates to undergo decomposition, the different categories are: easily decomposable, difficult to decompose, recalcitrant to decompose. Waste, discarded and useless materials without any value can be either solid, liquid, or mixed in nature. Nonbiodegradable wastes, mainly are synthetic in nature and are difficult to decompose. The alternate option with nonbiodegradable wastes is to subject them for recycling preceded by separation of their elements [Bhansali, 2021; Lee 2018; Singh, 2021; Tigtag, 2023]. The present work discusses here in brief the process of organic matter decomposition and its importance in rice straw breakdown and lignocellulosic material decomposition.

ORGANIC MATTER DECOMPOSITION

The breakdown of organic molecules is an important contributor to the ecosystem respiration and recycler of energy and nutrients in the ecosystem. The process along with the process of photosynthesis controls net carbon emission from the ecosystems. The process involves biochemical transformation in breakdown of complex substrates to the simpler forms [Ravn et al., 2020; Smith and Smith, 2012]. The dead plant remains in soil or plant litter is mineralized

and transformed to organic matter through the activities of soil microorganisms. Conversion of litter to organic matter involves many steps including the site and soil characteristics. Roots and Arbuscular Mycorrhizal fungi (AM) fungi are one of the key players in litter decomposition. These contribute to lignin, melanin and glycoproteins as the prime constituents. Litter transformation occurs along a gradient from above ground soil to the below ground soil, wherein aboveground litter is converted to humus [Prescott and Vesterdal, 2021]. Herein, the rate of decomposition of leaf tissue happens faster than the stem or wood decomposition [Middleton, 2020]. However, the climate plays a crucial role in litter decomposition [Joly et al., 2023]. Light is a vital factor in semi-arid ecosystems to lead litter decomposition [Austin and Vivanco, 2006]. The rate and course of litter decomposition influences biomass, nutrient and physico-chemical properties of the soil [Kumar et al., 2010].

ROTTING, FERMENTATION AND DECOMPOSITION: DIFFERENCES INVOLVED

Decomposition, a term related to ecology is a process of microbial digestion and destruction of dead material by the microbial process. Fermentation, a metabolic process and controlled process of decomposition as well as a microbial process dependent on enzymes varies with in composition of the involved enzymes to those of decomposition process involved enzymes [Surstromming, 2023]. In contrast, rotting, a state of decaying is an uncontrolled act of decomposition [Fermenters kitchen, 2023; Lakna, 2022]. The process of composting involves decomposition, and fermentation or putrefaction (anaerobic process) is an alternative suggestive to the process of composting (aerobic process) [Feed Innovation Services, 2013; Merfield, 2013; Organko, 2022; Chesapeake Bay Foundation, 2023; BioBag International AS, 2023].

FACTORS INVOLVED

Physico-Chemical

Composting, a process is dependent upon different factors, like microbial composition and succession, particle size and surface area of the particle, moisture content, aeration, temperature, volume of the material, C:N ratio, pH, etc. [Master Gardener, 2023; Nsimbe et al., 2018; Meena et al., 2021].

Substrate

Substrate quality depends upon the rate of microbial activity in organic matter decomposition. Flow of C and N to silt and clay fractions depends on the quality of substrate. The process leads to increased C and N residence times [Cyle et al., 2016]. Rate of decomposition reduces with ageing of litter and dead plant, animal residues and other substrates are decomposed till the point wherein they are no more recognizable and referred to at that stage as soil organic matter. The process of litter decomposition depends upon the interlinked action of three driving variables: physico-chemical environment, resource quality and decomposer organisms. [Doe and Johnson, 2009; Cotrufo et al., 2010]. Furthermore, administration of antibiotic alternatives in decomposition leads to a change in litter bacterial flora, and elevate the abundance of beneficial bacteria and reduce pathogen prevalence [Pedroso et al., 2014]. The other important factor that plays role in decomposition is climate [Joly et al., 2023]. In contrast, soil organic matter can be protected from decomposition physically and chemically. Additionally, low temperature and C: N ratio, lesser number of decomposers apart from large scale spatial

separation brings down the rate of decomposition [Nivethadevi et al., 2021]. Activity of extra-cellular enzymes in organic matter decomposition depends on substrate quantity and availability. Variation in enzymes is also an important factor here. Substrate affinity of enzymes varies with the temperature sensitivity for polymer hydrolysis and monomer oxidation [Myachina and Blagodatskaya, 2015]. In shrub ecosystems, effect of nitrogen addition in litter decomposition remains neutral due to the effect of low temperature and phosphorus limitation. Additionally, exogenous nitrogen inhibits lignin degradation but promotes breakdown of readily decomposed litter components [Zhang et al., 2021].

In a summary, substrate availability and decomposer community limits organic matter breakdown [Wutzler and Reichstein, 2008]. Oxidation of the carbon compounds provides energy to the decomposers. Breakdown of organic matter is a crucial requirement for energy and nutrient cycling in the ecosystem food web as well as contributor to the ecosystem respiration [Ravn et al., 2020; Middleton, 2020]. With the increase in recalcitrant chemical components in the litter, decomposability rate of litter decreases, and the decrease in decomposability or substrate quality is a complex process involving direct chemical changes in the substrate itself and microbial succession in biochemical reactions. Once, the limit value in decomposition is reached, the process will be proceeding towards a more stabilized soil organic matter. Thus, at higher initial nitrogen concentrations, C/N ratio comes down, least amount of organic matter is left over, indicating a stage of stabilized soil organic matter, low decomposition rate and lower mass loss [BERG, 2000]. Substrates vary with regard to their ease of decomposition, and in the scale from very rapid decomposable to slow decomposable, substrates are: (i) sugars, starches and simple proteins, (ii) crude proteins, (iii) hemicelluloses, (iv) celluloses, (v) fat, waxes, resins, (vi) lignin [Musa, 2023]. Shrub litter decomposes than the tree litter [Carnevale and Pablo, 2001] [25]. However, breakdown of organic matter helps in release of nutrients and functioning of the food web [FAO, 2023]. Additionally, climate indirectly affects litter decomposition by interacting with plant physiology and plant resorption, affecting chemical composition of the litter at its formative stages [Suseela, 2019]. Quality and quantity of the litter defines ecosystem functioning which in turn depends on plant species, forest structures, seasons and climate factors apart from soil drainage [Giweta, 2020; Schneckner et al., 2019; Krishna and Mohan, 2017; Certini et al., 2015; Kumar et al., 2010].

Biological: Enzymes & Microorganisms

The process of composting involves both aerobic and anaerobic microorganisms [FAO, 2023]. There is also involvement of thermophilic bacteria, fungi and actinomycetes [Joseph, 2019]. Thermophilic bacteria succeed mesophilic bacteria. Actinomycetes plays role in breakdown of materials like newspaper, bark, and other lingo-cellulosic materials. Apart from actinomycetes, mould and yeasts also help in breakdown of lingo-cellulosic materials. Additionally, protozoa consume inactive bacteria, fungi and actinomycetes. There are other physical decomposers also which feed on the organic waste [Editors, 2022]. Furthermore, there are different kinds of enzymes, like cellulases, hemicellulases, ligninase, chitinases and esterases, etc. with varied activities that play a role in composting [Finore et al., 2023; Nakamura et al., 2004; Murugesan and Amarnath, 2020; Infinita Biotech]. Lignin modifying enzymes from different producers acts at the compost maturity stage [Robledo-Mahon, 2020]. These activities lead to a change in concentrations of minerals in compost [Bohacz, 2019]. The mesophilic stage also has the

presence of bacteroides and proteobacteria as the dominant flora apart from the presence of bacteria, fungi, etc. [Biyada et al., 2021; Li et al., 2019; Rath et al., 2022].

BREAKDOWN OF LIGNOCELLULOSIC MATERIALS

Lignocellulose, component of a waste biomass breaks down when acted upon by the lignocellulose-degrading enzymes; cellulases, hemicellulases, laccases and ligninases [Chandra and Madakka, 2019]. Lignocellulosic material consists of cellulose, hemicellulose and lignin, wherein cellulose is a homopolymer of glucose residues, and lignin is a complex polymer of phenylpropane [Sahay, 2022]. The main source of lignocellulosic materials is plant biomass, and apart from fungi as the primary degraders, bacteria also play an important role as the potential degraders [deSouza, 2013; Wilhelm et al., 2019]. Lignocelluloses also act as a matrix wherein enzymatic hydrolysis for biofuel production occurs [Baig, 2020]. Microbial synergistic consortia of a thermophilic filamentous fungus and thermophilic actinobacterium has been reported to act as lignocellulose degraders [Shi et al., 2020]. Pretreatment of lignocellulosic materials also plays role in generation of fermentable sugars [Kucharska et al., 2018]. The best degraders of lignin in nature are the basidiomycetes white-rot fungi, followed by the brown rot fungi. Enzymes that play role in the lignin breakdown are namely, laccases, manganese-dependent peroxidases (MnP), lignin peroxidases (LiP), and versatile peroxidases (VP) [Andlar et al., 2018]. A complex bacterial consortium with species of Actinobacteria, Proteobacteria, bacilli, Sphingobacteria, and Flavobacteria in an enrichment culture system has been seen to breakdown different forms of lignocellulose [Georgiadou et al., 2021]. Furthermore, soil invertebrates also play a role in lignocellulose breakdown [Bredon et al., 2018]. The complex structure of lignocellulose needs participation and interaction of a variety of microorganisms. This also highlights upon the importance of conducting more research to elucidate the collaborative degradation mechanisms [Zhu et al., 2021].

BENEFITS OF ORGANIC MATTER DECOMPOSITION

Organic matter decomposition leads not only to the formation of humus, but also provides compost that improves soil structure, add plant nutrients and beneficial microorganisms to the soil. Addition of antibiotic, or antibiotic alternative helps to enrich beneficial microbes in the litter and compost [Pedroso et al., 2014]. Long term administration of compost to soil helps in improving the soil structure. Rice straw rich in ligno-cellulose when subjected to composting improves not only the microbial diversity, but also the grain yield and grain quality [Huang et al., 2023]. Paddy straw when left over in the field can neither be used as food or feed, but can be composted to generate a compost of better quality as well as return back of nutrients to the field [Nghie et al., 2020; Singh et al., 1995]. This helps also in generation of effective lignocellulose degraders [Goyal and Sindhu, 2011; Shruti et al., 2015]. Lignocellulosic biomass upon degradation leads also to the generation of high value products [Cecilia et al., 2021].

CONCLUSION

Organic matter decomposition involves the stages of: photo-oxidation, leaching, comminution and mineralization and depends on a number of interacting processes [Schowalter, 2016; Wantzen et al., 2008]. Composting is a process that speeds up the natural process of decomposition in presence of microorganisms [Albright and Martiny, 2018]. Paddy straw composting not only increases microbial activity and rate of composting but also improves the

degrading microflora [Jusoh et al., 2013, Nghi et al., 2020; Huang et al., 2023]. Enrichment of the process with cellulolytic bacteria in paddy cultivation led to an improved and better rice yield [Lestari et al., 2020]. The process of organic matter decomposition is understood experimentally from the view point of composting and humus formation. Thus, composting as a process highlights also upon the discovery of more efficient lignocellulose degraders, apart from helping to improve the soil quality and enrich the soil with beneficial nutrients and microflora.

References

- Texas A&M Agrilife Extension. 2023. Chapter 1, The decomposition process. <https://aggie-horticulture.tamu.edu/earthkind/landscape/dont-bag-it/chapter-1-the-decomposition-process/>
- UtahState University. 2023. Decomposition. <https://www.usu.edu/herbarium/education/fun-facts-about-fungi/decomposition>
- Bhansali R. 2021. An overview of non-biodegradable waste management and solutions. <https://organicbiotech.com/an-overview-of-non-biodegradable-waste-management-and-solutions/>
- Lee K. 2018. What are the effects of non-biodegradable waste? <https://sciencing.com/effects-nonbiodegradable-waste-8452084.html>
- Singh U. 2021. Non-biodegradable waste: A threat that demands immediate attention. <https://blog.ziploan.in/non-biodegradable-waste/>
- Tigtag. 2023. Natural and synthetic materials. <https://www.tigtagworld.co.uk/film/biodegradable-and-non-biodegradable-materials-PRM00612/>
- Ravn NR., Michelsen A., Reboleira ASPS. 2020. Decomposition of Organic Matter in Caves. *Front. Ecol. Evol.* 8:554651. doi: 10.3389/fevo.2020.554651
- Smith TM., Smith RL. 2012. "Decomposition and nutrient cycling," in *Elements of Ecology*, 8th Edn, ed. B. Wilbur (London: Pearson Education Inc).
- Prescott CE., Vesterdal L., 2021. Decomposition and transformations along the continuum from litter to soil organic matter in forest soils, *Forest Ecology and Management*, Volume 498, 2021, 119522, ISSN 0378-1127. <https://doi.org/10.1016/j.foreco.2021.119522>.
- Middleton BA. 2020. Trends of litter decomposition and soil organic matter stocks across forested swamp environments of the southeastern US. *PLoS ONE* 15(1): e0226998. <https://doi.org/10.1371/journal.pone.0226998>
- Joly FX., Scherer-Lorenzen M., Hättenschwiler S. 2023. Resolving the intricate role of climate in litter decomposition. *Nat Ecol Evol* 7, 214–223. <https://doi.org/10.1038/s41559-022-01948-z>
- Austin A., Vivanco L. 2006. Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. *Nature* 442, 555–558. <https://doi.org/10.1038/nature05038>
- Kumar J.I.N., Sajish PR., Kumar RN., Bhoi RK., 2010. Wood and leaf litter decomposition and nutrient release from *Tectona grandis* Linn. F. in a tropical dry deciduous forest of Rajasthan, Western India. *Journal of Forest Science*. 26(1): 17-23.

The Swedish Surstromming Supplier. 2023. Fermentation vs decomposition.
<https://www.surstromming.com/fermentation-vs-decomposition.html>

Fermenters Kitchen. 2023. What's the difference between fermenting and rotting food?
<https://fermenterskitchen.com/difference-fermenting-and-rotting/>

Lakna. 2022. What is the difference between fermentation and rotting? <https://pediaa.com/what-is-the-difference-between-fermentation-and-rotting/>

Feed Innovation Services. 2013. Fermentation vs composting.
https://provinos.nl/images/Fermentation_versus_composting.pdf

Merfield CN. (2013). Treating food preparation 'waste' by Bokashi fermentation vs. composting for crop land application: A feasibility and scoping review. Lincoln, New Zealand: The BHU Future Farming Centre: 23

Organko B. 2022. Composting vs Fermentation: let's start the discussion. <https://bokashiorganko.com/bokashi-library/composting-vs-fermentation>

Chesapeake Bay Foundation. 2023. Neighborhood Discovery: Decomposers and composting.
<https://www.cbf.org/document-library/education-resources/composting-investigation.pdf>

BioBag International AS. 2023. Composting. <https://biobagworld.com/environment/composting/>

Master Gardener. 2023. Composting Guide. <https://www.fast-growing-trees.com/pages/factors-that-affect-composting>

Nsimbe P, Mendoza H, Wafula ST, Ndejjo R. 2018. Factors Associated with Composting of Solid Waste at Household Level in Masaka Municipality, Central Uganda. *J Environ Public Health*. 2018:1284234. <https://doi.org/10.1155/2018/1284234>. PMID: 30581477; PMCID: PMC6276455.

Meena AL, Karwal M, Dutta D, Mishra RP. 2021. Composting: phases and factors responsible for efficient and improved composting. *Agriculture & Food: E-Newsletter*. 3(1) Article ID: 10028.

Cyle KT, Hill N, Young K, Jenkins T, Hancock D, Schroeder PA, Thompson A. 2016. Substrate quality influences organic matter accumulation in the soil silt and clay fraction. *Soil Biology and Biochemistry*. 103: 138-148. <https://doi.org/10.1016/j.soilbio.2016.08.014>

Fuji-Doe D, Johnson K. 2009. Litter and soil organic matter decomposition.
https://www.ctahr.hawaii.edu/littonc/PDFs/680_Discussion_LitterDecomp.pdf

Cotrufo M, Galdo I, Piermatteo D. 2010. Litter decomposition: Concepts, methods and future perspectives. In W. Kutsch, M. Bahn, & A. Heinemeyer (Eds.), *Soil Carbon Dynamics: An Integrated Methodology* (pp. 76-90). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511711794.006

Pedroso AA, Collett SR, Hurley-Bacon AL, Zedek AS, Lee MD. 2014. The potential of antibiotic alternatives for enriching beneficial microbiota in litter. *SOJ Microbiology and Infectious Diseases*. 2(2): 1-11.

Joly, F-X, Scherer-Lorenzen, M, Hättenschwiler, S, 2023. Resolving the intricate role of climate in litter decomposition. *Nature Ecology and Evolution*. <https://doi.org/10.1038/s41559-022-01948-z>

Nivethadevi P, Swaminathan C, Kannan P. 2021. Soil organic matter decomposition-roles, factors and mechanisms. In: *Latest trends in soil science Volume -1* (Eds. Sukul Singh Porte). Integrated Publications, New Delhi. Pp. 61-91.

Myachina O., Blagodatskaya E. 2015. Substrate-dependent temperature sensitivity of soil organic matter decomposition. *Geophysical Research Abstracts*. Vol. 17, EGU2015-15032.

Zhang J, Li H, Zhang H, Zhang H and Tang Z (2021) Responses of litter decomposition and nutrient dynamics to nitrogen addition in temperate shrublands of North China. *Front. Plant Sci.* 11:618675. doi: 10.3389/fpls.2020.618675

Wutzler T., Reichstein M. 2008. Colimitation of decomposition by substrate and decomposers – a comparison of model formulations. *Biogeosciences*. 5: 749-759. www.biogeosciences.net/5/749/2008/

Ravn NR, Michelsen A and Reboleira ASPS (2020). Decomposition of Organic Matter in Caves. *Front. Ecol. Evol.* 8:554651. <https://doi.org/10.3389/fevo.2020.554651>

Middleton BA. 2020. Trends of litter decomposition and soil organic matter stocks across forested swamp environments of the southeastern US. *PLoS ONE* 15(1): e0226998. <https://doi.org/10.1371/journal.pone.0226998>

Berg B. 2000. Litter decomposition and organic matter turnover in northern forest soils. *Forest Ecology and Management*. 133(1-2): 13-22. [https://doi.org/10.1016/S0378-1127\(99\)00294-7](https://doi.org/10.1016/S0378-1127(99)00294-7)

Musa A. 2023. Basic process of organic matter decomposition-basic agricultural study. <https://agriculturistmusa.com/process-of-organic-matter-decomposition/>

Carnevale Nélide J., Pablo, LJ. 2001. Litterfall and organic matter decomposition in a seasonal forest of the eastern Chaco (Argentina). *Rev. biol. trop* [Internet] 49(1): 203-212. Available from: http://www.scielo.sa.cr/scielo.php?script=sci_arttext&pid=S0034-77442001000100019&lng=en.

FAO. 2023. Organic matter decomposition and the soil food web. <https://fao.org/3/a0100e/a1000e05.htm>
Suseela V. 2019. Potential roles of plant biochemistry in mediating ecosystem responses to warming and drought. In *Ecosystem consequences of soil warming*. {print litter 2}

Giweta M. 2020. Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: a review. *Journal of Ecology and Environment* (2020) 44:11. <https://doi.org/10.1186/s41610-020-0151-2>

Schnecker J., Bowles T., Hobbie EA., Smith RG., Grandy AS. 2019. Substrate quality and concentration control decomposition and microbial strategies in a model soil system. *Biogeochemistry*, 144: 47-59. <https://doi.org/10.1007/s10533-019-00571-8>

Krishna MP., Mahesh M. 2017. Litter decomposition in forest ecosystems: a review. *Energ. Ecol. Environ.* 2(4): 236-249. <https://doi.org/10.1007/s40974-017-0064-9>

Certini G., Vestgarden LS., Forte C., Strand LT. (2015). Litter decomposition rate and soil organic matter quality in a patchwork heathland of southern Norway. *SOIL*, 1, 207–216. <https://doi.org/10.5194/soil-1-207-2015>.

Kumar JIN., Sajish PR., Kumar RN., Bhoi RK., 2010. Wood and Leaf Litter Decomposition and Nutrient Release from *Tectona grandis* Linn. f. in a Tropical Dry Deciduous

Forest of Rajasthan, Western India. *Journal of forest Science*. 26(1): 17-23.

FAO. 2023. Composting process and techniques. <https://www.fao.org/3/y5104e/y5104e05.htm#:~:text=In%20this%20process%2C%20aerobic%20microorganisms,micro%2Dorganisms%20decompose%20them%20further.>

Joseph K. 2019. The Science of compost. <https://untamedscience.com/biology/ecology/ecology-articles/the-science-of-compost/>

Editors MN. 2022. Composting-methods, types, factors and importance. <https://microbiologynote.com/composting-methods/>

Finore I, Feola A., Russo L. et al. 2023. Thermophilic bacteria and their thermozymes in composting processes: a review. Chem. Biol. Technol. Agric. 10, 7. <https://doi.org/10.1186/s40538-023-00381-z>

Nakamura K, Haruta, S., Nguyen H.L., Ishii, M., Igarashi, Y. 2004. Enzyme production-based approach for determining the functions of microorganisms within a community. Applied and Environmental Microbiology. 70(6): 3329-3337. <https://doi.org/10.1128/AEM.70.6.3329-3337.2004>

Murugesan V., Amarnath DJ. 2020. Bio-process performance, evaluation of enzyme and non-enzyme mediated composting of vegetable market complex waste. Scientific Reports. 10:19801. <https://doi.org/10.1038/s41598-020-75766-3>

Infinita Biotech, 2023. Important enzymes involved in the composting process. <https://infinitabiotech.com/blog/important-enzymes-involved-in-the-composting-process/#:~:text=Racemases%2C%20epimerases%2C%20and%20intramolecular%20isomerases,to%20digest%20various%20isomeric%20bonds.>

Robledo-Mahón T, Calvo C, Aranda E. Enzymatic Potential of Bacteria and Fungi Isolates from the Sewage Sludge Composting Process. Applied Sciences. 2020; 10(21):7763. <https://doi.org/10.3390/app10217763>

Bohacz, J. 2019. Changes in mineral forms of nitrogen and sulfur and enzymatic activities during composting of lignocellulosic waste and chicken feathers. Environ Sci Pollut Res 26, 10333–10342. <https://doi.org/10.1007/s11356-019-04453-2>

Biyada S, Merzouki M, Dêmčenko T, Vasiliauskienė D, Ivanec-Goranina R, Urbonavičius J, Marčiulaitienė E, Vasarevičius S, Benlemlih M. 2021. Microbial community dynamics in the mesophilic and thermophilic phases of textile waste composting identified through next-generation sequencing. Sci Rep. 11(1): 23624. <https://doi.org/10.1038/s41598-021-03191-1>. PMID: 34880393; PMCID: PMC8654937.

Li Z., Yang Y., Xia Y., Wu T., Zhu J., Wang Z., Yang J., 2019. The succession pattern of bacterial diversity in compost using pig manure mixed with wood chips analyzed by 16S rRNA gene analysis. bioRxiv 674069; <https://doi.org/10.1101/674069>

Rath PP, Das K, Pattanaik S. 2022. Microbial activity during composting and plant growth impact: A Review. J Pure Appl Microbiol. 16(1): 63-73. <https://doi.org/10.22207/JPAM.16.1.53>

Chandra M.R.G.S., Madakka M. 2019. Chapter 11 - Comparative Biochemistry and Kinetics of Microbial Lignocellulolytic Enzymes. In: Recent Developments in Applied Microbiology and Biochemistry (Eds.) Viswanath Buddolla. Academic Press. Pages 147-159.

ISBN 9780128163283, <https://doi.org/10.1016/B978-0-12-816328-3.00011-8>.

Sahay, S. 2022. Chapter 10 - Deconstruction of lignocelluloses: potential biological approaches.

In: Handbook of Biofuels. (Eds): Sanjay Sahay. Academic Press. 2022. Pages 207-232. ISBN 9780128228104, <https://doi.org/10.1016/B978-0-12-822810-4.00010-5>.

de Souza, W. R. (2013). Microbial Degradation of Lignocellulosic Biomass. InTech.

<https://doi.org/10.5772/54325>

Wilhelm R.C., Singh R., Eltis, L.D. et al. Bacterial contributions to delignification and lignocellulose degradation in forest soils with metagenomic and quantitative stable isotope probing. *ISME J* 13, 413–429 (2019). <https://doi.org/10.1038/s41396-018-0279-6>

Baig, K.S. Interaction of enzymes with lignocellulosic materials: causes, mechanism and influencing factors. *Bioresour. Bioprocess.* 7, 21 (2020). <https://doi.org/10.1186/s40643-020-00310-0>

Shi Z., Han C., Zhang X., Tian L., Wang L. (2020). Novel synergistic mechanism for lignocellulose degradation by a thermophilic filamentous fungus and a thermophilic actinobacterium based on functional proteomics. *Front. Microbiol.* 11: 539438. <https://doi.org/10.3389/fmicb.2020.539438>

Kucharska K, Rybarczyk P, Hołowacz I, Łukajtis R, Glinka M, Kamiński M. Pretreatment of Lignocellulosic Materials as Substrates for Fermentation Processes. *Molecules.* 2018; 23(11):2937. <https://doi.org/10.3390/molecules23112937>

Andlar M, Rezić T, Mardetko N, Kracher D, Ludwig R, Šantek B. (2018). Lignocellulose degradation: An overview of fungi and fungal enzymes involved in lignocellulose degradation. *Eng Life Sci.* 18 (11): 768-778. <https://doi.org/10.1002/elsc.201800039>. PMID: 32624871; PMCID: PMC6999254.

Georgiadou DN, Avramidis P, Ioannou E, Hatzinikolaou DG. Microbial bioprospecting for lignocellulose degradation at a unique Greek environment. *Heliyon.* 2021 Jun 3;7(6): e07122. doi: 10.1016/j.heliyon.2021.e07122. PMID: 34141913; PMCID: PMC8187967.

Bredon, M., Dittmer, J., Noël, C. et al. Lignocellulose degradation at the holobiont level: teamwork in a keystone soil invertebrate. *Microbiome* 6, 162 (2018). <https://doi.org/10.1186/s40168-018-0536-y>

Zhu K., Liu T., Liu J., Cao X., Liu J., Wang J. 2021. Microbial degradation of lignocellulose. *AIP Conference Proceedings* 2350, 020040 (2021); <https://doi.org/10.1063/5.0048528>

Huang X., Wang H., Zou Y., Qiao C., Hao B., Shao Q. Wu W., Wu H., Zhao J., Ren, L. Rice straw composting improves the microbial diversity of paddy soils to stimulate the growth, yield, and grain quality of rice. *Sustainability* 2023, 15, 932. <https://doi.org/10.3390/su15020932>

Nghi NT. et al. (2020). Rice Straw-Based Composting. In: Gummert, M., Hung, N., Chivenge, P., Douthwaite, B. (eds) *Sustainable Rice Straw Management*. Springer, Cham. https://doi.org/10.1007/978-3-030-32373-8_3

Singh RB, Saha RC, Singh M, Chandra D, Shukla SG, Walli TK, Pradhan PK, Kessels HP. 1995. Rice straw-Its production and utilization in India. In: *Handbook for straw feeding systems* (Eds. Singh, K., and Schiere, J.B. ICAR, New Delhi, India.

Goyal S., Sindhu SS. 2011. Composting of rice straw using different inocula and analysis of compost quality. *Microbiology Journal* 1(4): 126-138. <https://doi.org/10.3923/mj.2011.126.138>

Shruti, Sharma A, Malik DK. 2015. Lignocellulose biomass degradation by microbial consortium isolated from harvested rice field. *International journal of current microbiology and applied sciences.* 4(9): 274-280.

Cecilia J.A., Jiménez-Gómez C.P., García-Sancho C., Maireles-Torres P. (2021). Microbial Degradation of Lignocellulosic Biomass to Obtain High Value-Added Products. In: Shah, S., Venkatramanan, V., Prasad, R. (eds) *Bio-valorization of Waste. Environmental and Microbial Biotechnology*. Springer, Singapore. https://doi.org/10.1007/978-981-15-9696-4_13

Schowalter TD. 2016. Decomposition and pedogenesis. In: Chapter 14 - Decomposition and Pedogenesis, Insect Ecology (Fourth Edition), Editor(s): Timothy D. Schowalter. Academic Press, Pages 477-510, ISBN 9780128030332, <https://doi.org/10.1016/B978-0-12-803033-2.00014-5>.

Wantzen KM., Yule, CM., Mathooko, JM., Pringle, CM. 2008. 3 - Organic Matter Processing in Tropical Streams. In: Aquatic Ecology, Tropical Stream Ecology, Editor(s): David Dudgeon. Academic Press. Pages 43-64. ISBN 9780120884490, <https://doi.org/10.1016/B978-012088449-0.50005-4>.

Albright MBN, Martiny JBH. 2018. Is Throwing an Apple Core Out of the Car Littering? —Microbial Communities in Natural Composting Front. Young Minds 6:13. doi:10.3389/frym.2018.00013

Jusoh ML, Manaf LA, Latiff PA. 2013. Composting of rice straw with effective microorganisms (EM) and its influence on compost quality. Iranian J Environ Health Sci Eng. 10(1):17. doi: 10.1186/1735-2746-10-17. PMID: 23390930; PMCID: PMC3608067.

Lestari Y, Maftu'ah E, Annisa W. 2020. Rice straw composting by cellulolytic bacteria isolate and its application on rice in acid sulfate soils. BIO Web Conf. 20 01006. <https://doi.org/10.1051/bioconf/20202001006>