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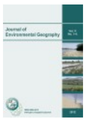

COMPOSTING OF DISTILLERY SPENT WASH

Lara Rúbia Borges Silva[1*], Levente Kardos[1]

[1]Hungarian University of Agriculture and Life Sciences, Institute of Environmental Sciences,
Department of Agro-environmental Studies, H-1118, Villányi út 29-43. Budapest, Hungary

*Corresponding author: borgesrubialara@gmail.com

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Abstract

Distillery spent wash, a by-product of the alcoholic beverage industry, is an organic waste whose management poses significant challenges due to its acidity, high organic load, notable content of polyphenols, macronutrients, micronutrients and heavy metals. In Europe, billions of liters of distillery waste are generated annually and its eco-unfriendly disposal can cause severe environmental and health impacts. Composting is a viable management strategy to treat and manage distillery slop promoting the recycling and stabilization of organic matter and nutrients in the material. The review examines different composting methods, such as single composting, co-composting and vermicomposting, along with their benefits and drawbacks. To optimize composting effectiveness, various materials, such as sewage sludge, vinasse, green and animal manure, inorganic amendments, bagasse, filter cake and municipal solid waste, among other agro-food and animal bio-wastes, can be used as a source of nitrogen and microorganisms. Also, the usage of different materials and mixtures aims to enhance the composting process increasing the degradation rate and the quality of the compost. The challenges of distillery spent wash composting are also covered in the paper which are mainly due to its characteristics, including high salt content, low carbon-to-nitrogen ratio, low pH and potential phytotoxicity. The paper concludes that composting distillery spent wash is an effective and sustainable waste management solution for recovering valuable nutrient resources and producing a stable nutrient-rich organic soil amendment. The produced compost can improve crop yields, nutrient absorption by plants and plant biomass and contribute to soil properties and restoration. The review provides insights into the current state of distillery spent wash composting and recommends future research directions to improve efficiency and expand potential applications.

Keywords: distillery spent wash, composting, organic waste, co-composting, vermicomposting

INTRODUCTION

Industries worldwide contribute to an acute energy crisis and environmental degradation through the generation of vast amounts of liquid, gaseous and solid waste resulting in significant environmental pollution. The conventional disposal methods of open dumping or landfilling are unsustainable due to the leaching of toxic chemicals and metals, leading to contamination of groundwater, soil and food resources. To address this issue, eco-friendly technologies are needed to manage industrial waste effectively while also being economically feasible and socially embraced (Suthar, 2007).

Alcohol distilleries have become one of the most polluting industries worldwide. They are currently experiencing significant global growth due to the wide-ranging applications of alcohol in various sectors, such as transportation, chemicals, pharmaceuticals and beverages (Maurya and Patil, 2018). Leading distillery-producing countries, according to Jernigan (2009), include China, India, the United States, Brazil, Russia and the United Kingdom.

According to Gebreeyessus et al. (2019), the distillery industry frequently utilizes locally available sugar sources, such as sugarcane molasses, in the production of alcoholic beverages through a sequential process of fermentation and distillation. Notably, India and Brazil primarily employ sugarcane and its byproduct, molasses, in sugar production, using them as the primary feedstock for alcohol production. Consequently, at the conclusion of the distillation process, a liquid residue or byproduct is generated, known as distillery spent wash (DSW). This byproduct can also be called spent mash, spent grain, vinasse, exhausted marc, slop, or stillage and it represents a part of the distillery wastewater that encompasses all liquid waste generated in the distillation process (Patel and Jamaluddin, 2018).

DSW presents significant challenges due to its complex, problematic and highly oxygen-demanding nature as an organic waste generated by industrial operations (Gebreeyessus et al., 2019). The distillery sector represents a substantial environmental burden because it converts a significant portion of its raw materials into waste, most of which is released into water bodies, resulting in water pollution. In India, as reported by Ravikumar (2007), approximately 88% of the raw materials used in distilleries become waste. Within distillery operations, it is estimated that about 15 liters of spent wash are generated and subsequently discharged for every liter of absolute-alcohol produced.

The disposal of DSW poses a substantial challenge due to its highly polluting nature which is characterized by elevated levels of both chemical oxygen demand (COD) and biochemical oxygen demand (BOD). This pollution results from the presence of diverse organic compounds, including polysaccharides, reduced sugars, lignin, proteins and waxes, in addition to a complex mixture of recalcitrant organic pollutants (Chowdhary et al., 2018). The recalcitrance is attributed to the existence of substances like melanoidins, polyphenols, brown polymers and various sugar decomposition products, including anthocyanin, tannins, steroids and different xenobiotic compounds, among others (Pandey et al., 2003; Patel and Jamaluddin, 2018). Furthermore, the spent wash contains inorganic substances such as nitrogen, potassium, phosphates, calcium and sulfates. It also exhibits additional concerning characteristics, including high salinity, a dark brown color, an unpleasant odor, low pH and the potential presence of heavy metals such as iron, zinc, nickel, manganese, lead, mercury, copper and chromium, along with an increased ash content. Importantly, these attributes are notably influenced by the choice of feedstock and the specifics of the distillation process, as emphasized by Kharayat (2012).

The proper management of distillery wastewater poses significant challenges for distilleries, scientists and the government entities. Physicochemical treatment methods can effectively remove organic pollutants but have drawbacks such as excessive use of chemicals, sludge generation, high operating costs and sensitivity to variable water intake. These methods may not be capable of removing certain contaminants like total dissolved solids and color to safe disposal limits (Satyawali and Balakrishnan, 2008). Therefore, an effective treatment of distillery wastewater may require a combination of physical (sedimentation, screening, aeration, filtration and floatation), chemical (chlorination, adsorption, ion exchange) and biological (anaerobic, aerobic processes) techniques. The major treatment methods for DSW include lagooning, anaerobic digestion with methane recovery, incineration and composting (Mohana et al., 2009; Maurya and Patil, 2018; Ray and Ghangrekar, 2019; Tiwari et al., 2019).

The discharge of DSW into water bodies has negative impacts on aquatic ecosystem. Firstly, the intense color of this wastewater reduces sunlight penetration leading to decreased oxygen production and harming aquatic life. Secondly, the high pollution load of DSW contributes to eutrophication which can deplete oxygen levels in water streams and pose a threat to aquatic flora and fauna. Distilleries have a significant role in meeting the demand for alcohol making eco-friendly management of DSW crucial. Therefore, sustainable treatment methods are necessary to prevent resource scarcity, protect human well-being and maintain environmental and ecosystem balance (Khalid et al., 2011).

Biotechnological processes offer effective solutions for treating organic waste including distillery waste. Kharayat (2012) demonstrated that these processes aim to remove biologically degradable organic compounds and color either by transforming them into valuable materials or eliminating harmful substances within the waste. Various methods such as anaerobic (e.g., bio-methanation) and aerobic biological treatments (e.g., trickling filters, activated sludge and aerated lagoon), composting, phytoremediation and fungal, algal, enzymatic and bacterial treatments are employed for high organic load wastes. Optimizing and identifying biotechnological treatment methods are crucial and previous studies have highlighted the potential of biological treatments for managing DSW (Kumar et al, 2020).

Composting has emerged as an effective biological approach for recovering resources from organic wastes, including DSW. It has proven to be successful in converting DSW into a stable and nutrient-rich soil conditioner. Compost improves soil organic matter and provides nutrients to nutrient-deficient soils, leading to increased crop yields and reduced irrigation requirements. The composting method has demonstrated its value as an organic amendment and is recognized as a beneficial practice (Haug, 1993; Kotroczó and Fekete, 2020).

This paper presents an overview of DSW composting, covering its composition, challenges and potential applications. It examines various composting strategies that have been researched and implemented for managing this challenging organic waste. The challenges associated with DSW composting and the potential uses of the resulting compost in sectors like agriculture as soil amendment are also discussed.

METHODOLOGY

The review was conducted following a systematic approach to ensure a comprehensive and unbiased assessment of the topic. The methodology involved the following steps:

Selection of databases and keywords:

Relevant literature on the composting of DSW was searched using electronic databases such as ScienceDirect, ResearchGate and Google Scholar. The keywords used for the search included “composting”, “co-composting”, “vermicomposting”, “biological treatment”, “distillation”, “distillery industry”, “distillery spent wash”, “vinasse”, “spent mash”, “distillery wastewater”, “distillery effluents”. The choice of keywords aimed to capture a wide range of studies related to the composting of DSW.

Inclusion and exclusion criteria:

A set of criteria was established to determine the eligibility of studies for inclusion in the review. Studies were included if they focused on the composting of DSW, provided detailed information on the composting process and reported relevant outcomes and findings.

Search strategy:

The search was conducted by combining the selected keywords using Boolean operators (AND, OR). The initial search generated a broad pool of articles related to composting, organic waste treatment and wastewater management. The search was then refined by incorporating specific terms related to distillery spent wash composting.

Article selection and data extraction:

The articles identified through the search were screened based on their titles and abstracts. The articles that met the inclusion criteria were then retrieved in full text for further evaluation. The data extraction process involved extracting relevant information, including study objectives, methodologies, key findings and conclusions.

Number of articles reviewed:

A total of 130 articles were initially identified through the literature search. After applying the inclusion and exclusion criteria, 86 articles were included in the review. The selection process involved multiple reviewers to ensure consistency and minimize bias.

By following this methodology, a comprehensive overview of the composting of DSW was obtained, incorporating relevant studies that provided valuable insights into the topic.

OVERVIEW OF DISTILLERY SPENT WASH

Distillery spent wash (DSW) is a byproduct of distillation process and is primarily associated with the production of alcoholic beverages like whiskey, rum, vodka and other spirits. However, it can also be generated in other industrial processes that involve alcohol production, such as certain biofuel production methods. Consequently, while it is most commonly linked to the alcoholic beverage industry, its generation may extend to other industrial processes involving alcohol fermentation and further distillation (Wagh and Nemade, 2018). As previously mentioned, it presents substantial environmental challenges when not managed properly. DSW is characterized by its high organic content, dark brown color and unpleasant odors, making it a complex and problematic effluent to handle.

Ray (2019) emphasized that the wastewater generated by distillery industries which utilize starch-based raw materials such as rice, barley, wheat, maize and potato, or cellulose-based materials such as sugarcane molasses, contains higher percentage of less rapidly degrading organic matter. Alcohol production in distilleries typically encompasses four stages: feed preparation, fermentation, distillation and packaging, according to Kharayat (2012). In continuous processes, cellulosic materials first undergo delignification, followed by acid hydrolysis of hemicellulose and cellulose, effectively transforming them into simpler sugars. These sugars are then transferred to fermentation tanks, diluted with water, inoculated with yeast cultures and supplemented with essential nutrients, ultimately resulting in the production of ethanol, carbon dioxide, among other compounds (Kharayat, 2012).

After the fermentation process, the fermented mash yields approximately 7.5% to 9% alcohol and subsequently, a distillation process is employed to recover the aqueous alcohol as distillate. Further purification of the concentrated alcohol is accomplished through a method called rectification. Distilleries commonly utilize a technique referred to as Multi-Pressure Distillation which combines both pressure and vacuum to extract the Rectified Spirit (RS) or Extra Neutral Alcohol (ENA) from the fermented mash (Kamble et al., 2017).

The generation of distillery spent wash occurs in the first column following the fermenter, known as the analyzer column, where preheated fermented mash is stripped of all volatile compounds, including ethyl-alcohol. Typically, the analyzer column is equipped with a degasser section at the top which removes all dissolved gases from the fermented mash. It generally operates under a vacuum to prevent scaling and reduce energy consumption. The vapors produced in this column, containing 45% to 55% ethanol vapors, are condensed and directed to the rectifier column which operates under elevated pressure (Shinde et al., 2020; Stichlmair et al., 2021).

According to Kharayat (2012), the standard volume of spent wash generated during the distillation process in a 1,000-liter distillery is 491.9 liters, with a specific generation rate of 11.9 liters of wastewater produced per liter of alcohol.

Composition and characteristics of distillery spent wash

DSW is a complex mixture of organic and inorganic compounds that results from the fermentation and distillation processes in alcohol production. Its composition varies depending on the type of raw materials and production methods (Wedzicha and Kaputo, 1992; Pant and Adholeya, 2006, 2007).

DSW is rich in organic matter containing high concentrations of sugars, alcohols, organic acids and nitrogenous compounds. It has a high chemical oxygen demand (COD) and biochemical oxygen demand (BOD) making it highly polluting if discharged untreated. Moreover, its dark brown color and offensive odors make it visually and olfactorily unpleasant. The distinctive color of DSW primarily arises from a persistent substance known as melanoidin, constituting around 2% of DSW derived from molasses (Yadav and Chandra, 2012). It is worth highlighting that these compounds, as observed by Kitts et al. (1993), exhibit antioxidant characteristics that make them detrimental to many microorganisms typically encountered in wastewater treatment processes.

Table 1 displays specific characteristics of distillery spent wash based on sugarcane molasses. This table was adapted from the table supplied by Kharayat (2012).

Table.1 Typical characteristics of distillery spent wash. (Source: Kharayat, 2012)

Parameters	Color	pH	Alkalinity [mg/L]	Total Solids [mg/L]	Suspended Solids [mg/L]	BOD [mg/L]	COD [mg/L]
Spent wash	Dark brown	4 – 4.5	3500	100,000	10,000	45,000 – 60,000	80,000 – 120,000

Challenges associated with distillery spent wash management.

Various methods are currently in use for the treatment of DSW to ensure its proper disposal. These methods encompass physical, chemical, physicochemical and biological techniques. As demonstrated by Kharayat (2012), the choice of treatment approach depends on several factors, including treatment effectiveness, associated costs, geographical and climatic conditions, land usage, regulatory compliance and the level of public acceptance of the treatment methods.

The challenges associated with DSW treatment are mainly due to its high organic load, acidic nature, presence of recalcitrant compounds, nutrient imbalance, unpleasant odors, material coloration, high moisture content and regulatory compliance. Notably, DSW's moisture content is exceptionally high, exceeding 90%, as confirmed by measurements conducted by Melamane et al. (2007), Ali et al. (2015a) and Anusha and Vagish (2022). This elevated moisture level complicates the composting process since successful composting typically requires a moisture content of approximately 55%. The solution involves blending the spent wash with bulking agents. As described by Iqbal (2010), bulking agents are typically fibrous materials with low moisture content, optimizing available air space while regulating the water content within the waste intended for composting.

Furthermore, the organic matter in DSW can deplete oxygen in water bodies, leading to adverse effects on aquatic ecosystems while its high nutrient content can cause eutrophication, disrupting aquatic biodiversity. The presence of unpleasant odors and the dark brown color make direct disposal undesirable and non-compliance with environmental regulations can result in legal consequences for distilleries (Pinamonti et al., 1997; Karaca, 2004). Therefore, proper management and treatment of DSW are essential to protect water resources, maintain ecological balance and ensure sustainable practices within the distillery industry.

To address these challenges, effective treatment methods, such as composting, have been explored to mitigate the environmental impact of DSW and transform it into valuable resources.

PRINCIPLES OF COMPOSTING

Composting is a natural biological process that involves the controlled decomposition of organic waste materials, such as DSW. This process relies on the activity of microorganisms, including bacteria and fungi, which break down the organic matter in DSW, transforming it into stable organic material and pathogen-free compost (Haug, 1993). This paper focuses on aerobic composting which aligns with Haug's insights on the composting process.

Yu et al. (2015) stated that anaerobic composting provides the advantage of reducing nitrogen loss, but it is important to acknowledge the limitations and disadvantages of this method. In comparison, aerobic composting offers several benefits over anaerobic composting. These advantages encompass a more rapid decomposition of raw materials, the elevation of pile temperatures to levels inhospitable to pathogens and weeds, a significant reduction of formation and emission of greenhouse gases and the capacity to generate compost in a relatively short period (Zeng et al., 2012; Gill et al., 2014).

Compost is the main product generated by composting and it can be characterized by being an organic soil conditioner that has been stabilized to an organic matter-rich product, a material free of human and plant pathogens and that is beneficial to plant growth. The production of compost follows three steps, as cited by Diaz et al. (2007): “(1) an initial, rapid stage of decomposition, (2) a stage of stabilization and (3) an incomplete process of humification”. Humification is the transformation of organic matter in the composting input materials into a more stable and long-lasting form, enriching soil quality and fertility. Additionally, the resulting compost offers several advantages, including resource recovery, increased crop yields, utility as a valuable soil additive, and reduced irrigation demands (Haug, 1993; Kotroczó and Fekete, 2020).

Composting offers various benefits, primarily by transforming the input materials into a more stable product known as compost. The use of compost as a soil amendment can significantly enhance several soil properties, including water content, water retention, aggregation, soil aeration, permeability, water infiltration, cation exchange capacity, pH buffering, resilience, carbon sequestration, among others and also reduces surface crusting (Pinamonti and Zorzi, 1996). According to Polprasert (2007), sandy and clayey soils experience the most significant improvements in their physical properties when amended with compost.

The composting process requires specific conditions to produce high-quality compost. These conditions include having enough organic matter as a substrate for microbial decomposition, maintaining an optimal balanced carbon-to-nitrogen (C/N) ratio, providing adequate moisture content, controlling temperature within mesophilic and thermophilic ranges, ensuring proper aeration for aerobic composting, maintaining an optimal pH range and achieving compost stability and maturity. These principles optimize microbial activity, decomposition efficiency, nutrient availability, odor control and the transformation of organic materials into stable compost (Bertran et al., 2004; Kotroczó and Fekete, 2020).

Composting of DSW can have both positive and negative environmental impacts. While composting is generally seen as an eco-friendly waste management approach, there are specific considerations when it comes to DSW. These include concerns about greenhouse gas emissions, leachate generation and odors. Mitigation strategies involve optimizing composting conditions, addressing leachate management and implementing odor control measures (Barthod et al., 2018). Challenges include regulatory compliance, technology and infrastructure requirements, nutrient management, public perception and the need for research and development. By collaborating, investing and taking proactive measures, it is possible to minimize environmental impacts and promote sustainable composting of DSW.

Composting techniques for DSW vary depending on factors such as feedstock, scale and control of key composting conditions (e.g., aeration, temperature, humidity). Windrow composting is a technique that involves forming long piles of organic material on a composting pad, periodically turning them for aeration and uniform decomposition. This technique is suitable for large-scale composting in agricultural and industrial settings. Static pile composting, on the other hand, involves forming compost piles without regular turning, allowing natural decomposition. It is simpler and suitable for smaller-scale operations, although it has slower composting and potential for anaerobic conditions and odor generation. Moreover, in-vessel composting uses enclosed containers with aeration systems for controlled decomposition and offers better temperature and moisture control, odor control and the ability to handle larger volumes of organic waste. However, it requires specialized equipment and higher capital investment (Haug, 1993; Diaz et al., 2007).

Tiwari et al. (2019) focused on the utilization of DSW through aerobic composting where it proved more efficient and resulted in compost with higher levels of organic carbon, nitrogen, phosphorus and potassium making it a valuable nutrient source for crops. Composting also aids in the degradation of colored organic matter in distillery effluents enriching the compost with essential nutrients. The utilization of DSW through composting offers an environmentally friendly alternative to inorganic fertilizers in agriculture.

Hence, composting is a practical solution for the waste management issue, especially for organic wastes, e.g., DSW, due to the biological stabilization of this material (Gómez-Brandón et al., 2011). Furthermore, this biological management also extends the lifespan of disposal sites, reducing the quantity of waste disposed and improving leaching control both in terms of quantity and quality.

Factors influencing composting of distillery spent wash

The composting performance of DSW is influenced by several factors that can be optimized to improve the process (Burg et al., 2014). These factors include the carbon-to-nitrogen (C/N) ratio, moisture content, temperature, aeration, microbial activity, pH, inhibitory substances, particle size, mixing and nutrient availability.

Maintaining a balanced C/N ratio, typically around 25–40:1, promotes microbial activity and efficient decomposition. Adequate moisture levels, ranging from 50% to 65%, are necessary for microbial growth and activity (Rynk et al., 2022). Controlling the temperature within thermophilic (50–70°C) or mesophilic (30–45°C) ranges supports decomposition and pathogen reduction and proper aeration ensures oxygen supply, preventing anaerobic conditions and promoting aerobic microbial activity (Haug, 1993; Bustamante et al., 2008a).

Microorganisms play a crucial role in composting and a diverse microbial community with the right mix of bacteria, fungi and actinomycetes is necessary for effective decomposition. Factors such as organic matter availability, moisture, temperature and oxygen levels influence microbial activity. Maintaining favorable conditions for microbial growth and activity is vital for optimal composting performance. Moreover, pH is an important parameter affecting composting performance with an optimal range of 5.5 to 8.0. Extreme pH values, such as the acidic nature of DSW, can inhibit microbial activity and impact decomposition (Diaz et al., 2007). Adjustments may be required using additives such as lime-rich materials to create a suitable pH environment.

DSW may contain inhibitory substances such as residual alcohol, organic acids, phenolic compounds and toxic metals which can hinder microbial activity and delay decomposition. Pre-treatment methods like dilution, detoxification or adjusting the pH and C/N ratio can help mitigate the inhibitory effects of these substances (Chowdhary et al, 2018).

To address the essential factors influencing the composting process, including variables like pH, temperature, microbial activity, nutrient balance, moisture levels and aeration, a variety of substances can be introduced into the initial materials. As indicated by research from Barthod et al. (2018), some of these added substances are known as bulking agents, primarily affecting the physical composition of the compost, especially its aeration, e.g., straw, stalk, wood chips, saw dust, rice hulls, etc. However, more often than not, these substances also exert direct or indirect effects on other aspects of the composting process and can thus be classified as additives. Additives play a pivotal role in improving the composting process by reducing leaching and gas emissions, enhancing the aeration within the compost, expediting the decomposition of organic matter and boosting the nutrient content and availability in the final compost product. It's worth noting that only a limited number of studies have explored the influence of additives on vermicomposting, as demonstrated in works by Wang et al. (2014), Barthod et al. (2016) and Malińska et al. (2017).

Substrates and additives in composting can be categorized into three groups, according to Doublet et al. (2011). Firstly, organic additives include materials like straw, mature compost, grass clippings, cornstalk and biochar, which is gaining interest as highly stabilized organic additive for composting and vermicomposting. When choosing organic additives, attention must be paid to the C/N ratio of the initial mixtures to ensure organic matter degradation and prevent nitrogen leaching during composting (Dias et al., 2010; Waqas et al., 2017). Secondly, the main inorganic or mineral additives comprise lime, clays and industrial by-products like red mud and fly ash, offering cost-effective and readily available options with properties to potentially adsorb heavy metals. Pure minerals like clay are increasingly used to reduce greenhouse gas emissions during composting and occasionally in vermicomposting (Barthod et al., 2016; Gomes et al., 2016). Lastly, biological additives involve microorganisms isolated from composts, cultivated and sold as commercial solutions for inoculating compost or vermicompost piles.

Particle size and proper mixing of DSW and bulking agents influence composting performance. Optimal particle size allows for aeration, moisture retention and microbial colonization while adequate mixing ensures uniform distribution of organic matter and promotes decomposition. Moreover, nutrient availability, including carbon, nitrogen, phosphorus and micronutrients, affects composting performance (Diaz et al., 2007; Rynk et al., 2022). Adjusting the C/N ratio using suitable bulking agents or co-composting materials helps create an optimal nutrient balance for microbial activity. Regular monitoring and control of composting parameters such as temperature, moisture content, pH, oxygen levels and nutrient content are essential for optimizing performance (Haug, 1993). Adjustments can be made to maintain optimal conditions throughout the composting process.

Improving the performance of composting and the quality of the final compost product from DSW can be achieved through a comprehensive understanding and management of the various factors already mentioned in this paper. An effective approach involves optimizing the composting process, such as by introducing biodegradable materials to achieve the ideal carbon-to-nitrogen (C/N) ratio. This optimization has the potential to expand the range of applications for recycled products and reduce unpleasant odors associated with factors like pH or C/N ratio (Fernández et al., 2008). Ultimately, this can enable the efficient and sustainable conversion of DSW into a valuable resource.

Vermicomposting: a composting method

One composting technique that can be used on DSW is vermicomposting that utilizes earthworms to decompose organic materials into nutrient-rich vermicompost (Ali et al., 2015b). Earthworms consume the waste and produce castings which further break down and enrich the compost. This process enhances microbial activity, nutrient release and organic compound breakdown. Vermicomposting can be done in worm beds or bins maintaining specific conditions for earthworm growth (Dominguez et al., 1997). It offers advantages such as rapid decomposition, flexibility in space usage and high-quality vermicompost production. However, it may be limited to smaller-scale operations and requires specific conditions. The resulting vermicompost can be used as a soil amendment to enhance plant growth and soil health. Vermicomposting is considered a sustainable and efficient method for DSW treatment, yielding high-quality end-product.

CASE STUDIES AND BEST PRACTICES IN COMPOSTING DISTILLERY SPENT WASH

There are several composting methods for DSW already researched and protocoled worldwide. In this study, we emphasize aerobic composting due to its well-established advantages, as previously discussed, when compared to anaerobic methods. Most research concerning DSW composting can be categorized into two primary methods based on the composition of the initial organic materials (feedstock): single composting and co-composting. Additionally, both methods may incorporate vermicomposting as an auxiliary composting technique. This chapter examines different research articles that focus on the composting of DSW.

Single composting

Single composting involves the natural decomposition of a single type of organic waste material, in this case DSW, through microbial activity. In this process, DSW can be mixed with inorganic amendments, bulking agents or additives to adjust pH, improve nutrient availability, reduce odor generation and enhance compost stability (Barthod et al., 2018). However, the excessive use of inorganic amendments should be carefully managed to avoid nutrient imbalances and potential environmental impacts.

In a study by Silva and Kardos (2022), composting of Pálinka spent wash, a byproduct of traditional Hungarian fruit spirit production, was examined. The main challenge was its low pH (around 4), effectively neutralized by composting with mineral additives like alginite and andesite. Excess moisture was managed by allowing evaporation. These additives produced valuable compost, improving decomposition and synthesis reactions. Furthermore, mature spent wash compost demonstrated heavy metal (iron and lead) adsorption potential, particularly when used as a growing medium for lettuce and tomato plants in culture vessel experiments. This research enhances our understanding of Pálinka spent wash composting and its potential for waste recycling and heavy metal adsorption and remediation applications.

The research paper by Hanc et al. (2019) examined the vermicomposting of distillery residues using the wheat straw as bulking agent in a vertical-flow windrow system. They found that the top layer of the compost had high humidity, electrical conductivity and earthworm biomass. It contained partially decomposed organic matter with favorable nutrient ratios. In contrast, the lower layers were more mature and had lower microbial activity, nutrient content and alkaline pH. Potassium was the most abundant macronutrient and phosphorus and magnesium increased with compost age. The top layer was suitable for starting new composting cycles and preparing extracts, while the older layers made a suitable organic fertilizer.

he study executed by Gomez-Brandón et al. (2023) investigated the use of vermicomposting to recycle and utilize distilled grape marc, a by-product of the winery industry. During a 56-day pilot-scale trial it was found that the marc provided suitable conditions for earthworm growth with increasing earthworm density and biomass. The pH levels and electrical conductivity of the marc also indicated optimal conditions for vermicomposting. After 14 days microbial activity decreased and the content of total polyphenols declined, suggesting stabilization. The resulting vermicompost met quality criteria for nutrient content and demonstrated its potential for environmentally friendly waste management and fertilizer production.

Co-composting

Co-composting is a method that involves combining two or more organic waste materials during composting to improve the process and produce high-quality compost. It utilizes different waste streams like DSW, sewage sludge, manure, vinasse and more to address nutrient imbalances, enhance moisture retention and promote microbial diversity (Giagnoni et al., 2020). Co-composting is conducted in specialized facilities with controlled processes to ensure optimal decomposition and compost quality.

Co-composting DSW with sewage sludge facilitates the decomposition of DSW and offers benefits such as increased nutrient content, especially nitrogen, improved stability of the compost and enhanced microbial activity. However, there are challenges to consider including the effective management of the C/N ratio, potential heavy metal contamination from sewage sludge and compliance with regulatory guidelines for sludge utilization.

Bustamante et al. (2007) conducted a composting study using winery and distillery wastes, including grape stalk and marc (GS and GM), wine lees (WL) and exhausted grape marc (EGM), with the Rutgers static pile composting system. This method, which controls temperature and relies on effective heat removal through ventilation, significantly accelerated the composting process compared to conventional methods (Finstein et al., 1992). The experiment involved two composting piles (pile 1 and pile 2) containing mixtures of GS, GM, EGM and sewage sludge (SS). Vinasse (V) was only added to pile 1 and its addition led to increased temperature, organic carbon degradation, electrical conductivity and cation exchange capacity. Eventually, both piles achieved stabilized organic matter with reduced phytotoxicity.

Another research undertaken by Bustamante et al. (2008a) investigated the changes in microbial indicators and pathogen levels during the co-composting of winery and distillery wastes with sewage sludge, cow and poultry manure. Various pile mixtures and composting systems (including the Rutgers system and turning system) were examined, with one pile being applied vinasse. The study monitored microbial indicators such as sulphite reducers clostridia, total enterobacteriaceae, total coliforms, faecal coliforms (*Escherichia coli*), enterococci, *Staphylococcus aureus* and *Salmonella spp*. The results showed that the static aerated piles which experienced relatively high temperatures of 50-60°C, were more effective in reducing pathogen content compared to the piles prepared using the turning system. The elevated temperatures contributed to a significant decrease in microbial groups like total and faecal coliforms (*E. coli*). However, it was observed that the characteristics of the raw materials used had a notable influence on the pathogen levels in the final compost product.

Vinasse, the final by-product of biomass distillation, originates from sugar crops (like beet and sugarcane), starch crops (including corn, wheat, rice and cassava), or cellulosic materials (such as crop residues, sugarcane bagasse and wood (Christofoletti et al., 2013). It is primarily generated during the distillation phase of ethanol fermentation, often serving as a liquid fertilizer in sugarcane cultivation and for irrigation due to its water retention properties. However, it has drawbacks, including greenhouse gas emissions, soil and groundwater pollution due to pH reduction (Devi et al., 2020). To improve composting, vinasse can be co-composted, providing extra nutrients and moisture (Madejón et al., 2001). Yet, its high organic load and moisture content may require additional bulking agents and precise moisture level monitoring during composting.

In the article by Madejón et al. (2001), two composts were produced through the co-composting of concentrated depotassified beet vinasse and two agricultural solid residues with distinct organic matter characteristics: spent grape marc as a lignin waste and cotton gin trash as a cellulosic waste. The composting process took place in aerated piles with mechanical turning under controlled conditions for a duration of four months. Temperature, pH and inorganic nitrogen changes exhibited similar trends for both mixtures. However, variations in organic matter fractions differed depending on the co-composted material. The use of spent grape marc as a bulking agent resulted in lower degradation of organic matter due to its high lignin content. No phytotoxicity was observed in the final compost products. The chemical and physical properties of both vinasse composts indicate their potential utilization as fertilizers.

The study by Diaz et al (2002) focused on optimizing the co-composting process of vinasse and spent grape marc. Various mixtures with increasing amounts of vinasse were incubated under aerobic conditions. The results showed that the pH values did not differ significantly among the mixtures. Mixtures with lower vinasse content had higher organic matter losses and greater biodegradability. The addition of vinasse increased the stability of the substrate-microorganism complex. However, higher vinasse ratios led to reduced microbial activity due to increased salinity and decreased pH. The study suggests that a moderate amount of vinasse, between 10% and 20%, is the best compromise for optimal co-composting.

Tejada et al. (2009) investigated the effects of co-composting beet vinasse with vermicompost on soil properties, loss and restoration. It was found that the use of organic-rich waste as an alternative or complement to mineral fertilizers is environmentally beneficial, provided that the organic wastes are not heavily polluted. In the case of fresh beet vinasse, it had a negative effect on the soil's physical, chemical and biological properties, leading to increased soil loss and decreased plant cover. This negative impact was attributed to the high levels of monovalent cations, such as Na+, present in beet vinasse which destabilized the soil structure. The study aimed to assess the effects of co-composting beet vinasse with vermicompost made from green forages on soil properties and its potential contribution to soil loss and restoration. The experiment was conducted over three years in a semiarid region in Spain. The results showed that co-composting had a positive impact on the soil improving its physical, chemical and biological properties. It resulted in reduced soil loss by 31.2% and increased plant cover by 68.7% both compared to unamended soil. These findings suggest that the co-composting of beet vinasse with vermicompost is beneficial for soil protection and restoration making it a promising approach for recovering semiarid areas.

The research paper by Romero et al. (2007) examined the effects of vermicomposting on winery and distillery wastes. Three different substrates, spent grape marc (SGM), a mixture of SGM and lees cake (SGML) and a mixture of biosolid vinasse and vine shoots (BvS), were vermicomposted for 8 months using *Eisenia andrei* worms. The process resulted in changes in the substrates' chemical composition and the humic acid-like (HAL) fractions. Vermicomposting reduced the total organic carbon content and C/N ratio while increasing total extractable carbon and humic acid carbon. The HAL fractions in the initial substrates were characterized by specific properties, but after vermicomposting they became more similar to soil humic acids. This transformation involved a decrease in certain components and an increase in oxygenated and acidic groups. Vermicomposting was found to be a suitable method for enhancing the quality of winery and distillery wastes as soil organic amendments with the mixture SGML showing slightly better results than SGM.

Nogales et al. (2005) explored the vermicomposting of various winery wastes (spent grape marc, vinasse biosolids, lees cakes and vine shoots) into valuable agricultural products using the earthworm species *Eisenia andrei*. The vermicomposting process effectively biodegraded the winery wastes and also improved their agronomic value by reducing the C/N ratio, conductivity and phytotoxicity while increasing the levels of humic materials, nutrients and pH. This suggests that winery wastes have potential as raw substrates for vermicomposting, although further research is needed for large-scale implementation.

Co-composting DSW with green and animal manure offers advantages such as improved compost quality, a balanced C/N ratio, enhanced nutrient content and increased microbial diversity. Challenges may stem from the availability and management of sufficient quantities of green and animal manure. Animal manure may carry antibiotic resistance determinants, pathogens and parasites that could potentially contaminate the compost. Green manure may contain plant pathogens and weed seeds, leading to lower-quality compost and potential pest infestation (Dandeniya and Caucci, 2020).

Pinter et al. (2019) investigated the effects of adding goat manure, garden leaves and alfalfa to exhausted grape marc during composting, as well as the influence of a plastic cover on the process and compost quality. They found that the compost made from the mixture of these materials had higher levels of nutrients compared to compost made solely from grape marc. The plastic cover did not significantly affect the compost's physicochemical properties but did impact the composition of microorganisms. All composts showed stability and were free of pathogens. A plant growth experiment indicated that all composts had suitable quality with the mixture compost performing the best. The study suggests that using a plastic cover can reduce microorganism content, while composting diverse organic residues can enhance microbiological activity and improve compost quality.

The analysis performed by Bustamante et al. (2008b) described the recycling of solid wastes from the winery and distillery industry through co-composting with animal manures. They created compost piles using exhausted grape marc and either cattle manure or poultry manure. Various parameters were monitored during the composting process including pH, organic matter, nitrogen forms, humification indices and phytotoxic compounds. The results showed that organic matter degraded following a specific pattern and composting effectively reduced phytotoxic compounds. The compost obtained were stable, humified and suitable for agricultural use. Overall, co-composting proved to be a viable method for recycling and treating these wastes.

Additionally, Bustamante et al. (2009) conducted a study on co-composting winery and distillery waste, utilizing multivariate techniques to identify essential parameters for describing the composting process. Their research highlighted the potential of these techniques in enhancing composting practices. The study found that co-composting with other residues such as sewage sludge, cattle manure and poultry manure as already described in Bustamante et al. (2007, 2008a, 2008b) produced mature compost. Multivariate methods also reduced the number of components required to evaluate compost quality through identification of four main variables (associated with compost maturity and humification, related to the compost's agronomic attributes, concerning solubility parameters and associated with ammonia and temperature changes). Moreover, linear discriminant analysis allowed the classification of organic materials based on their characteristics, regardless of their source.

Torres-Climent et al. (2015) conducted a study with the objective of evaluating the co-composting of winery and distillery wastes in combination with animal manures. Traditional chemical methods alone were insufficient to understand the humification process, so advanced instrumental techniques were employed. Three compost piles were created and analyzed using thermal analysis, Fourier Transform Infrared Spectroscopy (FT-IR) and Cross-Polarization Magic Angle Spinning Carbon-13 Nuclear Magnetic Resonance (CPMAS 13C NMR). The results showed that the advanced techniques provided valuable information about the transformation of organic matter during composting. Thermal analysis estimated the degradability and stability of the compost samples, while FT-IR and CPMAS 13C NMR revealed variations in organic compounds and carbon structures. The combination of these methods offered insights into the composting process and the quality of the end-products.

The investigation carried out by Marhuenda-Egea et al. (2007) managed a study to explore the use of thermal analysis for characterizing chemical changes during composting of winery and distillery residues. They analyzed compost samples from three piles using techniques such as differential thermal analysis (DTA), thermogravimetry (TG) and the first derivative of TG (DTG). Pile 1, prepared with grape stalk, grape marc, exhausted grape marc and sewage sludge, showed different temperature patterns compared to piles 2 and 3 which used exhausted grape marc with cow manure and grape marc with poultry manure, respectively. Pile 1 appeared to be poorly composted. The researchers used CO_2 ion current curves and DTG curves to distinguish between well-stabilized (piles 2 and 3) and poorly stabilized (pile 1) organic matter. Energy release calculations and weight loss data provided insights into the composting process and helped determine the optimal point for compost harvest potentially reducing the overall composting time.

Suthar (2007) investigated the use of *Eisenia fetida* earthworms to stabilize sludge from a sugar industry distillation unit mixed with cattle manure. Different mixtures of these materials were tested under laboratory conditions for 90 days. The resulting vermicompost showed improvements in various parameters including optimal pH and increased nitrogen, phosphorus, potassium, calcium and magnesium content. The earthworms effectively decomposed the mixture, particularly with lower proportions of distillery sludge. The study also found a reduction in extractable metals. Earthworm growth and reproduction were highest with 20% distillery sludge while higher proportions of sludge led to increased earthworm mortality. Vermicomposting can be a useful method for managing distillery sludge and producing nutrient-rich compost for land restoration. It also helps mitigate metal toxicity and reduces the risk of soil contamination from industrial waste.

In the study conducted by Singh et al. (2014), distillery sludge was treated through vermicomposting using *Eisenia fetida* to convert it into soil-enriching material. The sludge was mixed with cattle manure in varying ratios and the vermicomposting process was carried out with and without the presence of *Eisenia fetida*. The results showed that the presence of cattle manure positively influenced the survival rate, growth rate, maturity-onset, cocoon production and the population of earthworms. The optimal concentration of sludge for achieving the highest number of worms, cocoons and hatchlings was determined using a response surface design. Nitrogen, phosphorus, sodium and pH levels increased during vermicomposting, while they decreased in the absence of earthworms. Transition metal content increased in both cases, but organic carbon, electrical conductivity and potassium showed an opposite trend.

Bagasse, the primary solid by-product of sugar production, and filter cake, the principal solid waste, can both be co-composted with DSW. Sugarcane bagasse (SCB), as defined by Zhang and Sun (2016), consists of the fibrous remains left after crushing and juicing sugarcane stalks in raw sugar production. Filter cake, on the other hand, is formed during the clarification of sugarcane juice with calcium hydroxide and includes suspended matter from the original juice and inorganic salts that precipitate during clarification (George et al., 2010). In organic waste composting, SCB serves as a structural component, creating pores in the composting material to regulate moisture levels. Despite its acidic nature, an appropriate amount of SCB can effectively aid nutrient conversion by regulating pH levels in organic waste. These materials serve as bulking agents and provide additional carbon and microbial diversity. They also improve aeration, enhance compost structure and increase carbon content. However, the availability of bagasse and filter cake may depend on the local sugar industry limiting the applicability of this technique in some regions.

The article by Zhang and Sun (2016) explored the use of sugarcane bagasse and exhausted grape marc in composting green waste. The study found that adding a combination of 15% sugarcane bagasse and 20% exhausted grape marc improved composting conditions and resulted in high-quality compost. The optimized two-stage composting method allowed the compost to mature in just 21 days, much faster than traditional composting methods. This research highlights the potential for using lignocellulosic waste in composting to effectively dispose of waste while generating a valuable product.

he examination conducted by Wongkoon et al. (2014) aimed to study the decomposition of organic residues from sugar mills and alcohol factories, the properties of the resulting compost and its impact on sugarcane growth. The compost made from filter cake and distillery slop reached maturity within 45 days and showed increasing levels of organic matter and nitrogen-phosphorus-potassium (NPK) content over time. The use of KKU microbes in the compost resulted in better outcomes compared to commercial compost microbes. Supplementing the compost with chemical fertilizers improved sugarcane growth. Although the compost alone provided plant nutrients, better results were obtained when it was combined with NPK fertilizers.

The article by Sarangi et al. (2008) presented a method for rapidly composting sugar mill press mud and DSW using microbial culture. The compost generated from these materials exhibits favorable physicochemical characteristics and nutrient content, promoting healthy plant growth. Moreover, it has proven to be effective as a soil conditioner and nutrient replenisher for sustainable agriculture. The composting process effectively converted non-degradable components of the wastes, such as lignin and melanoidins into a stabilized organic matter, an essential soil component that enhances soil fertility and supports sustainable crop productivity.

The study conducted by Alavi et al. (2017) examined the efficiency of co-composting and vermicomposting of a mixture of vinasse, cow manure, chopped bagasse and natural zeolite. The composting process lasted for 60 days and utilized *Eisenia fetida* earthworms. The results indicated a decrease in the carbon-to-nitrogen ratio over time and an alkaline pH range for the final fertilizer. The total potassium content decreased while the total phosphorus content increased during the process. The compost showed a high germination index and a low cellular respiration maturity index suggesting its stability. Overall, the study concluded that the compost obtained from the co-composting and vermicomposting process could serve as a beneficial soil amendment.

Co-composting DSW with municipal solid waste entails integrating these components into the composting procedure. This not only provides structural support and aeration but also contributes to organic matter and a diverse microorganism population, resulting in several benefits. These advantages encompass heightened compost stability, increased carbon content and the effective utilization of solid waste resources. Nonetheless, potential challenges may emerge due to the presence of contaminants in municipal solid waste and the necessity for accurate waste segregation (Machado and Hettiarachchi, 2020).

The study by Fernández et al. (2008) investigated the co-composting of exhausted grape marc (EGM) with different organic wastes. Four piles were created: EGM (control); EGM mixed with cow manure and straw (CMS); EGM mixed with municipal solid waste (MSW) and EGM mixed with grape stalks (GS). The results showed that adding MSW and GS increased the rate constants of composting, while CMS reduced it. Co-composting reduced the remaining carbon concentration and increased the readily biodegradable carbon fraction. Only Piles 1 and 4 achieved thermal sanitization. The lowest nitrogen loss occurred when GS was added. The study recommended using GS as a co-substrate and bulking agent for co-composting with EGM.

In a study by Damodharan and Padmapriya (2022), they compared the composting of organic municipal solid waste with and without the addition of spent wash as an inoculum in a vertical aerobic bench-scale reactor. The use of spent wash was found to expedite the composting process. The study assessed various parameters, including carbon, nitrogen, phosphorous, carbon/nitrogen ratio, temperature and moisture content. Results indicated that incorporating spent wash improved compost quality, with increased nitrogen, phosphorous and potassium content, and a reduced C/N ratio, rendering the resulting compost suitable for use as a fertilizer. The pH levels, temperature and moisture content remained within acceptable ranges throughout the 15-day experiment. The study also identified prevalent bacteria species in the municipal solid waste, including *Enterococci sp*, *Bacillus sp* and *E. coli*. Overall, the inclusion of spent wash as an inoculum enhanced the composting process and elevated the quality of the resultant compost, making it a promising choice for future nutrient-enriched applications.

In conclusion, composting techniques for DSW have specific advantages and limitations that should be considered based on local conditions and material availability. Proper management practices, such as monitoring moisture levels and temperature, and ensuring adequate aeration and C/N ratio, are crucial for successful composting. Adherence to regulatory guidelines and quality standards is important for safe compost utilization. Co-composting and vermicomposting offer alternative approaches to traditional composting optimizing the process and enhancing compost quality. These methods maximize the utilization of DSW as a resource in sustainable agriculture and soil management. Notably, when selecting a composting technique for DSW treatment, factors such as the scale of operation, available resources, composition of input materials, local environmental conditions, regulatory compliance, quality standards and available technology should all be taken into careful consideration.

DISTILLERY SPENT WASH COMPOST

Composting DSW can result in high-quality compost with desirable characteristics. The process breaks down organic matter making nutrients more available for plants. It also forms stable compounds that enhance soil structure and fertility. Proper composting stabilizes pH benefiting soil conditions. Additionally, composting reduces pathogens and weed seeds ensuring the safety and quality of the compost. Overall, composting DSW produces nutrient-rich, humus-rich, pH-stable compost that promotes soil health and plant growth.

Several research papers have explored the applications of DSW compost, particularly its impact on crop yield and soil properties.

Villena et al. (2018) investigated the use of compost derived from winery and distillery waste in a melon crop. Different doses of compost were applied and the effects on plant growth, nutrient accumulation, fruit yield and quality were studied. The application of compost resulted in increased plant biomass and improved relative growth rate. Significant improvements in fruit yield were observed with a specific compost dose. The compost application was found to be environmentally safe and it enhanced fruit quality. Overall, the study demonstrated the positive impact of winery and distillery waste compost on melon crop performance.

The research by Bustamante et al. (2008c) investigated the use of composts made from distillery wastes as alternatives to peat in transplant production. Two types of compost were created using spent grape marc with either cattle or poultry manure. Different vegetable species were grown using various substrate mixtures containing peat and compost. The study found that the composts had suitable properties for use as growing media in horticulture. Composts from the co-composting of grape marc and cow/poultry manure were identified as viable substitutes for peat, with volumes of 25-50%, without compromising yield or nutritional outcomes compared to the control.

Paredes et al. (2007) focused on the composting of winery by-products, specifically exhausted grape marc (EGM) and vinasse and its potential as an organic amendment in agricultural soils. Composting EGM helps eliminate phytotoxicity and produce a stable end-product with beneficial nutrients. Previous studies have already shown positive effects of grape marc compost on plant growth. Then, this study aimed to examine the impact of EGM compost on soil nitrogen dynamics during horticultural crop growth. The results indicate that EGM compost application improves soil fertility by increasing organic nitrogen. However, there is low nitrogen mineralization and a period of nitrogen immobilization, particularly when EGM and poultry manure compost are used. Organic nitrogen losses from the composts are minimal. The mineralization of organic nitrogen in mature composts is influenced by crop nutrient demands. The application rate of EGM compost is appropriate, as it yields similar lettuce production to commercial values. It is recommended to apply EGM compost one month before planting to avoid nitrogen immobilization.

The research conducted by Tejada et al. (2008) investigated the effects of different treatments on the restoration of soil using beet vinasse (BV), uncomposted *Trifolium pratense L.* (TP) — a leguminous plant — and composted mixtures of TP and BV. The results showed that BV negatively impacted soil properties, including physical, chemical and biological aspects. It decreased structural stability, increased bulk density, raised exchangeable sodium percentage and decreased microbial biomass, soil respiration and enzymatic activities. In contrast, TP application had positive effects on soil physical and biological properties. When TP was co-composted with BV, especially at a 2:1 ratio, the resulting compost positively influenced soil properties. After four years, plant cover decreased in BV-amended plots but increased in TP and TP + BV compost treatments. These findings indicate that BV alone deteriorates the soil, while TP and TP composted with BV contribute to its restoration.

The study executed by Bustamante et al. (2011) aimed to investigate the impact of incorporating different organic materials into a calcareous vineyard soil over three growing seasons. The organic materials used included sheep manure and four composts derived from winery and distillery waste treatment. The application of these organic materials resulted in increased soil microbial activity, higher levels of soil macro and micronutrients and a gradual release of inorganic nitrogen. Overall, the study showed that incorporating winery and distillery waste composts had positive effects on the soil improving its characteristics and nutrient content.

Therefore, DSW compost offers numerous benefits and potential applications. It can be used as a soil amendment to enhance soil quality, fertility and structure. Compost provides slow-release organic nutrients reducing the need for synthetic fertilizers and supporting sustainable agriculture. It can also aid in land reclamation projects promoting vegetation growth and ecological recovery. DSW compost is valuable in horticulture and landscaping, improving soil fertility, plant growth and aesthetics. Additionally, it has potential for environmental remediation by assisting in the treatment of contaminated soils. However, adherence to regulatory guidelines and quality standards is crucial to ensure environmental and human health. It can be concluded that DSW compost contributes to sustainable waste management and the principles of circular economy.

CONCLUSION AND PERSPECTIVES

Distillery spent wash composting is a promising waste management technique with the potential to effectively convert this organic waste into a valuable resource. Nonetheless, as highlighted in this review, numerous factors influence the composting of DSW. Effectively managing these factors is crucial for successful composting.

Various composting techniques, such as co-composting and vermicomposting, have been employed for distillery spent wash (DSW) treatment. Co-composting, when used in combination with suitable substrates and additives, significantly improves the composting process, resulting in high-quality organic compost. Furthermore, DSW composting plays a vital role in reducing or eliminating recalcitrant compounds, pathogens and heavy metals from the input material, while simultaneously enhancing nutrient content, pH levels, soil organic matter, microbial populations and other factors discussed in this review. The resulting compost holds promise for various applications, including soil enhancement, use as a fertilizer and land reclamation projects.

Nonetheless, it's important to acknowledge that composting DSW can pose environmental challenges, including greenhouse gas emissions, leachate production and odor-related issues. To address these concerns, the implementation of proper management practices and effective mitigation strategies is essential. This can involve using specific substrates and additives to mitigate these issues, as well as leveraging the assistance of worms and microbial inoculation in the composting process. These steps are vital in ensuring that the benefits of DSW composting are maximized while minimizing its potential adverse impacts on the environment.

Lessons learned and best practices for composting DSW involve optimizing composting parameters, utilizing co-substrates in co-composting, investing in suitable technology and infrastructure, implementing effective odor management measures, ensuring quality control and testing and promoting research and development collaborations.

Furthermore, there are important implications and future research directions to consider. These include studying the dynamics of microbial communities during composting, optimizing process parameters for different types of DSW, establishing standardized guidelines and regulations, exploring innovative composting techniques and co-substrates, examining the socio-economic implications, conducting long-term monitoring studies to evaluate compost stability and its impact on different soil types, on soil properties and on crop yields.

In conclusion, composting offers a sustainable solution for managing distillery spent wash. Its optimization requires considering various factors, as detailed in this paper, and continuous research in the field. Exploring alternative methods, additives, diverse organic waste for co-composting, and employing aids such as worms and microbial inoculum are avenues worth pursuing. Through these improvements and a commitment to quality standards, the value and sustainability of distillery spent wash composting can be maximized, effectively addressing the management of this organic waste.

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REFERENCES

Alavi, N., Daneshpajou, M., Shirmardi, M., Goudarzi, G., Neisi, A., Babaei, A.A. 2017. Investigating the efficiency of co-composting and vermicomposting of vinasse with the mixture of cow manure wastes, bagasse, and natural zeolite. *Waste Management, 69,* 117–126. DOI: https://doi.org/10.1016/j.wasman.2017.07.039

Ali, N., Ayub, S., Ahmad, J. 2015a. A study on economic treatment of distillery effluent. *International Journal of Current Research and Review* 7(11), 8. DOI: https://doi.org/10.31782/2231-2196

Ali, U., Sajid, N., Khalid, A., Riaz, L., Rabbani, M.M., Syed, J.H., Malik, R.N. 2015b. A review on vermicomposting of organic wastes. *Environmental Progress & Sustainable Energy* 34(4), 1050-1062. DOI: https://doi.org/10.1002/ep.12100

Anusha, K.N., Vagish M. 2022. Study of organic constituents in distillery spent wash and primary treated distillery effluent (PTDE) with different dilutions. *International Journal for Research in Applied Science and Engineering Technology*. 10. DOI: https://doi.org/10.22214/ijraset.2022.47067

Barthod, J., Rumpel, C., Dignac, M.F. 2018. Composting with additives to improve organic amendments. A review. *Agron. Sustain. Dev.* 38, 17.DOI: https://doi.org/10.1007/s13593-018-0491-9

Barthod, J., Rumpel, C., Paradelo, R., Dignac, M.F. 2016. The effects of worms, clay and biochar on CO_2 emissions during production and soil application of co-composts. *Soil* 2, 673–683.DOI: https://doi.org/10.5194/soil-2-673-2016

Bertran, E., Sort, X., Soliva, M., Trillas, I. 2004. Composting winery waste: sludges and grape stalks. *Bioresource technology* 95(2), 203–208. DOI: https://doi.org/10.1016/j.biortech.2003.07.012

Burg, P., Pavel, Z., Milan, M. 2014. Evaluating of selected parameters of composting process by composting of grape pomace. *Acta Universitatis Agriculturae Et Silviculturae Mendelianae Brunensis* 59, 75–80. DOI: https://doi.org/10.11118/actaun201159060075

Bustamante, M.A., Moral, R., Paredes, C., Vargas-García, M.C., Suárez-Estrella, F., Moreno, J. 2008a. Evolution of the pathogen content during co-composting of winery and distillery wastes. *Bioresource Technology* 99(15), 7299–7306. DOI: https://doi.org/10.1016/j.biortech.2007.12.051

Bustamante, M.A., Paredes, C., Marhuenda-Egea, F.C., Pérez-Espinosa, A., Bernal, M.P. Moral, R. 2008b. Co-composting of distillery wastes with animal manures: carbon and nitrogen transformations in the evaluation of compost stability. *Chemosphere* 72(4), 551–557. DOI: https://doi.org/10.1016/j.chemosphere.2008.03.030

Bustamante, M.A., Paredes, C., Moral, R., Agulló, E., Pérez-Murcia, M. D., Abad, M. 2008c. Composts from distillery wastes as peat substitutes for transplant production. *Resources, Conservation and Recycling* 52(5), 792–799. DOI: https://doi.org/10.1016/j.resconrec.2007.11.005

Bustamante, M.A., Paredes, C., Moral, R., Moreno-Caselles, J., Pérez-Murcia, M.D., Pérez-Espinosa, A., Bernal, M.P. 2007. Co-composting of distillery and winery wastes with sewage sludge. *Water Science and Technology* 56(2), 187–192. DOI: https://doi.org/10.2166/wst.2007.488

Bustamante, M.A., Paredes, C., Morales, J., Mayoral, A.M., Moral, R. 2009. Study of the composting process of winery and distillery wastes using multivariate techniques. *Bioresource Technology* 100(20), 4766–4772. DOI: https://doi.org/10.1016/j.biortech.2009.04.033

Bustamante, M.A., Said-Pullicino, D., Agulló, E., Andreu, J., Paredes, C., Moral, R. 2011. Application of winery and distillery waste composts to a Jumilla (SE Spain) vineyard: effects on the characteristics of a calcareous sandy-loam soil. *Agriculture, Ecosystems and Environment* 140(1–2), 80–87. DOI: https://doi.org/10.1016/j.agee.2010.11.014

Chowdhary, P., Raj, A., Bharagava, R.N. 2018. Environmental pollution and health hazards from distillery wastewater and treatment approaches to combat the environmental threats: a review. *Chemosphere* 194, 229–246. DOI: https://doi.org/10.1016/j.chemosphere.2017.11.163

Christofoletti, C.A., Escher, J.P., Correia, J.E., Marinho, J.F.U., Fontanetti, C.S. 2013. Sugarcane vinasse: environmental implications of its use. *Waste management* 33(12), 2752–2761. DOI: https://doi.org/10.1016/j.wasman.2013.09.005

Damodharan, V., Padmapriya, J. 2022. Organic Fraction of Municipal Solid Waste Management with spent wash as inoculum and utilization of compost obtained. *Advances in Bioresearch* 13(2), 79–85. DOI: https://doi.org/10.15515/abr.0976-4585.13.2.7985

Dandeniya, W.S., Caucci, S. 2020. Composting in Sri Lanka: Policies, Practices, Challenges, and Emerging Concerns. In: Hettiarachchi, H., Caucci, S., Schwärzel, K. (eds): Organic Waste Composting through Nexus Thinking. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-36283-64

Devi, G.K., Vignesh, K., Chozhavendhan, S. 2020. Effective utilization of sugarcane trash for energy production. In: Refining biomass residues for sustainable energy and bioproducts (pp. 259–273). Academic Press. DOI: https://doi.org/10.1016/B978-0-12-818996-2.00012-0

Dias, B.O., Silva, C.A., Higashikawa, F.S., Roig, A., Sánchez-Monedero, M.A. 2010. Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. *Bioresour Technol* 101, 1239–1246. DOI: https://doi.org/10.1016/j.biortech.2009.09.024

Diaz, L.F., De Bertoldi, M., Bidlingmaier, W., Stentiford, E. 2007. Compost science and technology. Elsevier, Amsterdam/Boston, 364 p.

Diaz, M.J., Madejón E., López F., López R., Cabrera F. 2002. Optimization of the rate vinasse/grape marc for co-composting process. *Process Biochemistry* 37(10), 1143–1150. DOI: https://doi.org/10.1016/S0032-9592(01)00327-2

Dominguez, J., Edwards, C.A., Subler, S. 1997. A comparison of vermicomposting and composting. *Biocycle* 38, 57–59. Online available at https://jdguez.webs.uvigo.es/wp-content/uploads/2016/04/Comparison%20of%20vermicomposting%20and%20composting.pdf

Doublet, J., Francou, C., Poitrenaud, M., Houot, S. 2011. Influence of bulking agents on organic matter evolution during sewage sludge composting; consequences on compost organic matter stability and N availability. *Bioresource Technology* 102(2), 1298–1307. DOI: https://doi.org/10.1016/j.biortech.2010.08.065

Fernández, F.J., Sánchez-Arias, V., Villaseñor, J., Rodríguez, L. 2008. Evaluation of carbon degradation during co-composting of exhausted grape marc with different biowastes. *Chemosphere* 73 (5): 670–77. DOI: https://doi.org/10.1016/j.chemosphere.2008.07.007

Finstein, M.S., Miller, F.C., MacGregor, S.T., Psarianos, K.M. 1992. The Rutgers strategy for composting: process design and control. *Acta Hortic.* 302, 75–86. DOI: https://doi.org/10.17660/ActaHortic.1992.302.7

Gebreeyessus, G.D., Mekonnen, A., Alemayehu, E. 2019. A review on progresses and performances in distillery stillage management. *Journal of Cleaner Production* 232, 295–307. DOI: https://doi.org/10.1016/j.jclepro.2019.05.383

George, P.A.O., Eras, J.J.C., Gutierrez, A.S., Hens, L., Vandecasteele, C. 2010. Residue from sugarcane juice filtration (filter cake): energy use at the sugar factory. *Waste and Biomass Valorization* 1, 407–413. DOI: https://doi.org/10.1007/s12649-010-9046-2

Giagnoni, L., Martellini, T., Scodellini, R., Cincinelli, A., Renella, G. 2020. Co-composting: An Opportunity to Produce Compost with Designated Tailor-Made Properties. In: Hettiarachchi, H., Caucci, S., Schwärzel, K. (eds): Organic Waste Composting through Nexus Thinking. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-36283-6_9

Gill, S.S., Jana, A.M., Shrivastav, A. 2014. Aerobic bacterial degradation of kitchen waste: A review. *Journal of Microbiology, Biotechnology and Food Sciences* 3(6), 477–483.DOI: https://doi.org/10.15414/jmbfs.2014.3.6.477-483

Gomes, H.I., Mayes, W.M., Rogerson, M., Stewart, D.I., Burke, I.T. 2016. Alkaline residues and the environment: a review of impacts, management practices and opportunities. *Journal Cleaner Production* 112, 3571–3582. DOI: https://doi.org/10.1016/j.jclepro.2015.09.111

Gómez-Brandón, M, Lazcano, C., Lores, M., Domínguez, J. 2011. Short-term stabilization of grape marc through earthworms. *Journal of Hazardous Materials* 187(1–3), 291–295. DOI: https://doi.org/10.1016/j.jhazmat.2011.01.011

Gómez-Brandón, M., Lores, M., Domínguez, J. 2023. Recycling and valorization of distilled grape marc through vermicomposting: a pilot-scale study. *Journal of Material Cycles and Waste Management* 25(3), 1509–1518. DOI: https://doi.org/10.1007/s10163-023-01627-6

Hanc, A., Hrebeckova, T., Kuzel, S. 2019. Vermicomposting of distillery residues in a vertical-flow windrow system. *Waste and Biomass Valorization* 10(12), 3647–3657. DOI: https://doi.org/10.1007/s12649-019-00671-4

Haug, R.T. 1993. The practical handbook of compost engineering. Routledge. DOI: https://doi.org/10.1201/9780203736234

Iqbal, M.K., Shafiq, T., Ahmed, K. 2010. Characterization of bulking agents and its effects on physical properties of compost. *Bioresource Technology* 101(6), 1913–1919. DOI: https://doi.org/10.1016/j.biortech.2009.10.030

Jernigan, D.H. 2009. The global alcohol industry: an overview. *Addiction* 104, 6–12. DOI: https://doi.org/10.1111/j.1360-0443.2008.02430.x

Kamble, S.M., Dasar, G.V., Gundlur, S.S. 2017. Distillery spent wash production, treatment and utilization in agriculture - a review. *Int. J. Pure App. Biosci.* 5, 379–386. DOI: https://doi.org/10.18782/2320-7051.2840.

Karaca, A. 2004. Effect of organic wastes on the extractability of cadmium, copper, nickel, and zinc in soil. *Geoderma* 122(2–4), 297–303. DOI: https://doi.org/10.1016/j.geoderma.2004.01.016

Khalid, A., Arshad, M., Anjum, M., Mahmood, T., Dawson, L. 2011. The anaerobic digestion of solid organic waste. *Waste Management* 31(8), 1737–1744. DOI: https://doi.org/10.1016/j.wasman.2011.03.021

Kharayat, Y. 2012. Distillery wastewater: bioremediation approaches. *Journal of Integrative Environmental Sciences* 9(2), 69–91. DOI: https://doi.org/10.1080/1943815x.2012.688056

Kitts, D.D., Wu, C.H., Stich, H.F., Powrie, W.D. 1993. Effect of glucose-lysine Maillard reaction products on bacterial and mammalian cell mutagenesis. *Journal of Agricultural and Food Chemistry* 41(12), 2353–2358. DOI: https://doi.org/10.1021/jf00036a026

Kotroczó, Z., Fekete, I. 2020. Significance of soil respiration from biological activity in the degradation processes of different types of organic matter. *DRC Sustainable Future: Journal of Environment, Agriculture, and Energy* 1(2), 171–179. DOI: https://doi.org/10.37281/DRCSF/1.2.10

Kumar, V., Chandra, R., Thakur, I.S., Saxena, G., Shah, M. P. 2020. Recent advances in physicochemical and biological treatment approaches for distillery wastewater. *Combined application of physico-chemical and microbiological processes for industrial effluent treatment plant.* pp. 79–118. DOI: https://doi.org/10.1007/978-981-15-0497-6_6

Machado, C.R., Hettiarachchi, H. 2020. Composting as a Municipal Solid Waste Management Strategy: Lessons Learned from Cajicá, Colombia. In: Hettiarachchi, H., Caucci, S., Schwärzel, K. (eds): Organic Waste Composting through Nexus Thinking. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-36283-6_2

Madejón, E., Díaz, M.J., López, R., Cabrera, F. 2001. Co-composting of sugarbeet vinasse: influence of the organic matter nature of the bulking agents used. *Bioresource technology* 76(3), 275–278. DOI: https://doi.org/10.1016/S0960-8524(00)00126-7

Malińska, K., Golanska, M., Caceres, R., Rorat, A., Weisser, P., Ślęzak, E. 2017. Biochar amendment for integrated composting and vermicomposting of sewage sludge—the effect of biochar on the activity of *Eisenia fetida* and the obtained vermicompost. *Bioresour Technol* 225, 206–214. DOI: https://doi.org/10.1016/j.biortech.2016.11.049

Marhuenda-Egea, F.C., Martínez-Sabater, E., Jordá, J., Sánchez-Sánchez, A., Moral, R., Bustamante, M.A., Paredes, C., Pérez-Murcia, M.D. 2007. Evaluation of the aerobic composting process of winery and distillery residues by thermal methods. *Thermochimica Acta* 454(2), 135–143. DOI: https://doi.org/10.1016/j.tca.2007.01.015

Maurya, P.M., Patil, S.V. 2018. A review on treatment of distillery wastewater by physicochemical approaches. *International Journal of Research Studies in Science, Engineering and Technology* 5(9), 36–44.

Melamane, X.L., Strong, P.J., Burgess, J.E. 2007. Treatment of wine distillery wastewater: a review with emphasis on anaerobic membrane reactors. *South African Journal of Enology and Viticulture* 28(1), 25–36. DOI: https://doi.org/10.21548/28-1-1456

Mohana, S., Acharya, B.K., Madamwar, D. 2009. Distillery spent wash: treatment technologies and potential applications. *Journal of Hazardous Materials* 163(1), 12–25. DOI: https://doi.org/10.1016/j.jhazmat.2008.06.079

Nogales, R., Cifuentes, C., Benítez, E. 2005. Vermicomposting of winery wastes: a laboratory study. *Journal of Environmental Science and Health* Part B 40(4), 659–73. DOI: https://doi.org/10.1081/pfc-200061595

Pandey, R.A., Malhotra, S., Tankhiwale, A., Pande, S., Pathe, P.P., Kaul, S.N. 2003. Treatment of biologically treated distillery effluent - a case study. *International Journal of Environmental Studies* 60(3), 263–275. DOI: https://doi.org/10.1080/00207230290024270

Pant, D., Adholeya, A. 2006. Enhanced production of ligninolytic enzymes and decolorization of molasses distillery wastewater by fungi under solid state fermentation. *Biodegradation* 18(5), 647–659. DOI: https://doi.org/10.1007/s10532-006-9097-z

Pant, D., Adholeya, A. 2007. Biological approaches for treatment of distillery wastewater: a review. *Bioresource Technology* 98(12), 2321–2334. DOI: https://doi.org/10.1016/j.biortech.2006.09.027

Paredes, C., Medina, E., Moral, R., Bustamante, M.A., Perez-Espinosa, A. 2007. Nitrogen dynamics in a clayey loam soil amended with distillery waste compost. *14th Ramiran International Conference: Treatment and Use of Non-Conventional Organic Residues in Agriculture*. Onilne available at http://ramiran.uvlf.sk/ramiran2010/docs/Ramiran2010_0124_final.pdf

Patel, S., Jamaluddin, 2018. Treatment of distillery wastewater: a review. *International Journal of Theoretical and Applied Sciences* 10(1), 117–139.

Pinamonti, F.L., Stringari, G.I., Gasperi, F.L., Zorzi, G.I. 1997. The use of compost: its effects on heavy metal levels in soil and plants. *Resources, Conservation and Recycling* 21(2), 129–143. DOI: https://doi.org/10.1016/S0921-3449(97)00032-3

Pinamonti, F.L., Zorzi, G. 1996. Experiences of compost use in agriculture and in land reclamation projects. In: de Bertoldi, M., Sequi, P., Lemmes, B., Papi, T. (eds): The Science of Composting. Springer, Dordrecht. DOI: https://doi.org/10.1007/978-94-009-1569-5_49

Pinter, I.F., Fernández, A.S., Martínez, L.E., Riera, N., Fernández, M., Aguado, G.D., Uliarte, E.M. 2019. Exhausted grape marc and organic residues composting with polyethylene cover: process and quality evaluation as plant substrate. *Journal of Environmental Management* 246, 695–705. DOI: https://doi.org/10.1016/j.jenvman.2019.06.027.

Polprasert, C. 2007. Organic Waste Recycling Technology and Management. International Water Association (IWA), London, Vol. 101, 833–835.

Ravikumar, R. 2007. Biodegradation and decolourization of biomethanated distillery spent wash. *Indian Journal of Science and Technology* 1(2), 1–6. DOI: https://doi.org/10.17485/ijst/2008/v1i2/2

Ray, S.G., Ghangrekar, M.M. 2019. Comprehensive review on treatment of high-strength distillery wastewater in advanced physico-chemical and biological degradation pathways. *International Journal of Environmental Science and Technology* 16, 527–546. DOI: https://doi.org/10.1007/s13762-018-1786-8

Romero, E., Plaza, C., Senesi, N., Nogales, R., Polo, A. 2007. Humic acid-like fractions in raw and vermicomposted winery and distillery wastes. *Geoderma* 139(3–4), 397–406. DOI: https://doi.org/10.1016/j.geoderma.2007.03.009

Rynk, R., Schwarz, M., Richard, T.L., Cotton, M., Halbach, T., Siebert, S. 2022. Compost feedstocks. In: The Composting Handbook (pp. 103–157). Academic Press. DOI: https://doi.org/10.1016/B978-0-323-85602-7.00005-4

Sarangi, B.K., Mudliar, S.N., Bhatt, P., Kalve, S., Chakrabarti, T., Pandey, R.A. 2008. Compost from sugar mill press mud and distillery spent wash for sustainable agriculture. *Dynamic Soil, Dynamic Plant* 2(1), 35–49.

Satyawali, Y., Balakrishnan, M. 2008. Wastewater treatment in molasses-based alcohol distilleries for cod and color removal: a review. *Journal of Environmental Management* 86(3), 481–97. DOI: https://doi.org/10.1016/j.jenvman.2006.12.024

Shinde, P.A., Ukarde, T.M., Pandey, P.H., Pawar, H.S. 2020. Distillery spent wash: an emerging chemical pool for next generation sustainable distilleries. *Journal of Water Process Engineering* 36, 101353. DOI: https://doi.org/10.1016/j.jwpe.2020.101353

Silva, L.R.B., Kardos. L. 2022. Recycling of organic waste: an overview of Pálinka distillery mash composting. *Journal of Central*

European Green Innovation 10(Suppl 1), 157–75. DOI: https://doi.org/10.33038/jcegi.3509

Singh, J., Kaur, A., Vig, A. P. 2014. Bioremediation of distillery sludge into soil-enriching material through vermicomposting with the help of eisenia fetida. *Applied Biochemistry and Biotechnology* 174(4), 1403–1419. DOI: https://doi.org/10.1007/s12010-014-1116-7

Stichlmair, J.G., Klein, H., Rehfeldt, S. 2021. *Distillation: principles and practice.* New York, John Wiley & Sons, 688 p. DOI: https://doi.org/10.1002/9781119414674

Suthar, S. 2007. Bioremediation of aerobically treated distillery sludge mixed with cow dung by using an epigeic earthworm *Eisenia Fetida*. *The Environmentalist* 28(2), 76–84. DOI: https://doi.org/10.1007/s10669-007-9031-x

Tejada, M., García-Martínez, A.M., Parrado, J. 2009. Effects of a vermicompost composted with beet vinasse on soil properties, soil losses and soil restoration. *CATENA* 77(3), 238–247. DOI: https://doi.org/10.1016/j.catena.2009.01.004

Tejada, M., Gonzalez, J.L., García-Martínez, A.M., Parrado, J. 2008. Application of a green manure and green manure composted with beet vinasse on soil restoration: effects on soil properties. *Bioresource Technology* 99(11), 4949–4957. DOI: https://doi.org/10.1016/j.biortech.2007.09.026

Tiwari, A., Khalid, M.A., Garg, M. 2019. Spent-wash utilization in bio-composting: a sustainable solution. *International Journal of Research and Analytical Reviews (IJRAR)* 6(2), 399-404. Online available at http://www.ijrar.org/IJRAR19K8305.pdf

Torres-Climent, A., Gomis, P., Martín-Mata, J., Bustamante, M.A., Marhuenda-Egea, F.C., Pérez-Murcia, M.D., Pérez-Espinosa, A., Paredes, C., Moral, R. 2015. Chemical, Thermal and Spectroscopic Methods to Assess Biodegradation of Winery-Distillery Wastes During Composting. *Edited by Jorge Aburto. PLOS ONE* 10(9), e0138925. DOI: https://doi.org/10.1371/journal.pone.0138925

Villena, R., Castellanos, M.T., Cartagena, M.C., Ribas, F., Arce, A., Cabello, M.J., Requejo, M.I. 2018. Winery distillery waste compost effect on the performance of melon crop under field conditions. *Scientia Agricola* 75(6), 494–503. DOI: https://doi.org/10.1590/1678-992x-2016-0507.

Wagh, M.P., Nemade, P.D. 2018. Biogas generation from distillery spent wash by using an OPUR western biotechnology process: a case study. *Desalination and water treatment* 118, 241–248. DOI: https://doi.org/10.5004/dwt.2018.22404

Wang, J., Hu, Z., Xu, X., Jiang, X., Zheng, B., Liu, X., Pan, X., Kardol, P. 2014. Emissions of ammonia and greenhouse gases during combined pre-composting and vermicomposting of duck manure. *Waste Manag.* 34, 1546–1552. DOI: https://doi.org/10.1016/j.wasman.2014.04.010

Waqas, M., Nizami, A.S., Aburiazaiza, A.S., Barakat, M.A., Ismail, I.M.I., Rashid, M.I. 2017. Optimization of food waste compost with the use of biochar. *J Environ Manag.* 216, 70–81. DOI: https://doi.org/10.1016/j.jenvman.2017.06.015

Wedzicha, B.L., Kaputo, M.T. 1992. Melanoidins from glucose and glycine: composition, characteristics and reactivity towards sulphite ion. *Food Chemistry* 43(5), 359–367. DOI: https://doi.org/10.1016/0308-8146(92)90308-o.

Wongkoon, T., Boonlue, S., Riddech, N. 2017. Effect of compost made from filter cake and distillery slop on sugarcane growth. *Asia-Pacific Journal of Science and Technology* 19(Supplement issue), 250–255. Online available at https://so01.tci-thaijo.org/index.php/APST/article/view/83127

Yadav, S., Chandra, R. 2012. Biodegradation of organic compounds of molasses melanoidin (MM) from biomethanated distillery spent wash (BMDS) during the decolourisation by a potential bacterial consortium. *Biodegradation* 23, 609–620. DOI: https://doi.org/10.1007/s10532-012-9537-x

Yu, H., Jiang, J., Zhao, Q., Wang, K., Zhang, Y., Zheng, Z. and Hao, X. 2015. Bioelectrochemically-assisted anaerobic composting process enhancing compost maturity of dewatered sludge with synchronous electricity generation. *Bioresour. Technol.* 193, 1–7. DOI: https://doi.org/10.1016/j.biortech.2015.06.057

Zeng, J., Price, G.W., Arnold, P. 2012. Evaluation of an aerobic composting process for the management of Specified Risk Materials (SRM). *J. Hazard Mater.* 219, 260–266. DOI: https://doi.org/10.1016/j.jhazmat.2012.04.003

Zhang, L., Sun, X. 2016. Improving green waste composting by addition of sugarcane bagasse and exhausted grape marc. *Bioresource Technology* 218, 335–343. DOI: https://doi.org/10.1016/j.biortech.2016.06.097