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Review

Sugarcane Distillery Spent Wash (DSW) as a Bio-Nutrient Supplement: A Win-Win Option for Sustainable Crop Production

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Abstract: Industrial pollution has been continuously soaring and causing serious threats to the soil, water, and air quality. The increase in industrialization has not only covered the large areas, but also created a large quantity of wastewater which is difficult to handle. The water produced from different industries is getting its place in the agriculture. However, the challenge is to properly use wastewater, so that the application of wastewater does not cause any soil and environmental problems. The distillery spent wash (DSW) is a liquid waste that is produced from the sugarcane industry. It contains a large load of both organic and inorganic substances. Also, DSW contains a sufficient amount of macronutrients (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and Sulphur (S)) and micronutrients (zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn)), which in turn improves the growth and yield of crops. The optimized doses of DSW substantially improve soil enzymatic and microbial activities, organic carbon, nutrient uptake, soil porosity, water holding capacity, aggregate stability, and anti-oxidant activities, which in turn improve the photosynthetic efficiency, growth and yield. However, the inadequate knowledge about the DSW characteristics and methods of its agricultural application present questions concerning environmental quality for groundwater pollution. Therefore, to obtain a better understanding about the DWS, here, we discussed the effects of DSW on soil quality, crop yield, and its implications for agriculture and water quality.

Keywords: anti-oxidants; crop yield; DSW; microbial activities; photosynthesis; soil organic carbon

1. Introduction

Waste management is one of the mightiest challenges being faced across the globe. The rapid increase in industrialization has increased the quantities of wastewater, which is difficult and costly to handle. The composition of wastewater is considerably varied from one industry to another. Recently, the use of wastewater in agriculture raised the interest of agriculturalists and environmentalists. Moreover, wastewater can cater to the nutritional need for the crops with the additional benefits of improving soil quality and crop yield [1]. The sugarcane (*Saccharum officinarum* L.) industry is among the major agro-based industries making an appreciable contribution towards the socio-economic development of many countries. This industry is involved in the processing of sugarcane to produce sugar [2]. Additionally, this industry produced many byproducts such as bagasse, press mud and distillery spent wash (DSW).

Among these byproducts, DSW is produced in a large quantity and contains a huge organic load that makes it a potential source as an agricultural input. Also, DSW does not contain any toxic metal since it is a plant origin. In addition, it provides an appreciable number of macronutrients (i.e., N, K, S, P) and micronutrients (i.e., Fe, Cu, and Zn), whereas it contains a low quantity of heavy metals that comes from sugar production processing [3]. Therefore, the application of DSW to the agricultural lands can control the water pollution [3] with additional benefits to the soil properties and crop yield [4]. The DSW is an ideal nutrient source for the major crops and vegetables [4]. In a field study conducted in India, the diluted DSW significantly increased the cane and sugar yield compared to application of inorganic fertilizers and control (no fertilizer) [5]. Similarly, it was reported that DSW improved the growth, yield and chlorophyll contents [6] and resulted in an improvement in the photosynthesis and led to better production. Moreover, the application of diluted DSW on course textured sandy and calcareous soils increased the water holding capacity, nutrient holding capacities, and availability of different nutrients such as N, P, K, Zn, Fe, Cu, and Mn [5]. Therefore, the management of DSW will not only be instrumental for the environment, but will also provide additional benefits as a source of fertilizers for agriculture. Moreover, the optimized dose of DSW can reduce the accumulation of potential toxic elements in crops and soils [7] therefore, reduce health risks in humans. In the current review, we discussed the potential benefits of DWS on soil quality, nutrient uptake, crop yield, and its implications for agriculture, groundwater quality, and human health. However, many research gaps are pending in plant physiological and biochemical aspects in response to DSW. Therefore, these research gaps and future directions on the use of DSW are also discussed to make it an important agricultural input without compromising the environment.

2. Sugar Industry Wastewater

The sugar industry can be classified into three different types. The first type produces the raw sugar, the second type produces the ethanol, and the third type produces both sugar and ethanol. Most of the sugar industries are belong to the third category, and it has been reported that more than 80% of the sugar industries produce both sugar and ethanol across the globe [8]. Moreover, it was reported that 90% of the harvested sugarcane is used to produce only sugar and ethanol, while the remaining 3% and 7% are used for the sugar and ethanol preparation [9]. Generally, the sugar production process comprises different steps such as juice extraction and clarification, evaporation, crystallization and centrifugation. Moreover, the sugar manifesting process is usually divided into two types (i.e., carbonation and sulphidation) based on the utilization of the chemicals.

The agricultural sector and agro-based industries are considered the major users for the freshwater. For instance, the sugar industry needs a huge quantity of the freshwater to be used in the sugar manufacturing. They used freshwater in the various processes of the sugar production that becomes a wastewater and can be differed in terms of quality and quantity. The variations in the generation of the wastewater depend on the feedstock, products and different chemicals that are used in the manufacturing process. In sugar industries, wastewater is produced from the two different sources. In the first source, water is produced from different cane processing steps including evaporation, crystallization and refinery; whilst in the second source, wastewater is obtained from the condensers and the washing of chimneys [10]. Additionally, sugarcane that is used in the sugar industry can contain 70–80% moisture. Therefore, about 0.7–1.0 m^3 water can be produced by crushing

1 ton of the sugarcane [11,12], and 1–2 m^3 water can be used during the processing 1 ton of the sugarcane [13].

Moreover, water used for cleaning different sections of the sugar industry can generate a huge quantity of wastewater. Nonetheless, wastewater is mainly produced by washing, boiling, vacuum pans and centrifugation. In addition, during cleaning of the water tubes, SO_2 production house, descaling of heat exchangers and evaporators can produce a large volume of the wastewater [10]. The processing house and mill house are the main sections of the wastewater production in sugar production. The water produces from the mill houses is generally polluted with grease, oil and suspended solids, whereas the water produced from the processing unit has high pH, COD, BOD, and organic matter [11]. The studies conducted on the sugar industry wastewater documented that the quality of effluent depends upon the nature of the used sugarcane, chemicals used in the processing, and the soil characteristics where the sugarcane was grown [14].

In general, this wastewater creates serious environmental issues, if it is not properly managed. In developing countries, the management of this waste is considered as a big problem owing to the complex nature of the waste and the limited technological development. The sugar industry can be a major source of the water pollution due to the high presence of BOD, COD, sulfates, chloride, and nitrate [15,16]. Sugar mills wastewater contains high BOD and COD that can quickly deplete the oxygen in water bodies and can cause a risk for the aquatic life by interfering with the aquatic flora and fauna. Moreover, improper waste management can create a septic condition owing to the generation of the foul-smelling hydrogen sulfide, which can result in a precipitation of iron (Fe) as well as dissolve the salts that make water bodies black [17]. Further, the wastewater is considered unfit for humans and aquatic life [16,18]. Thus, the direct use of the sugar industry water without any treatment and dilution can negatively impact the crop productivity and the soil health.

3. Sugarcane Distillery Spent Wash

In the sugar industry, ethanol distillery is a major consumer for non-processing functions including cooling, steam generation, year propagation and molasses preparation [19]. The major portion of the wastewater is molasses which can be categorized as DSW, fermented sludge and spent less (Figure 1). The fermented wash is the major product of the fermentation process that can be poured, while the remained sludge is known as fermented sludge. This effluent that is released from the bottom of fermenters can contribute towards the pollution loads from the distillery. Thus, fermenter sludge is considered as a wastewater produced after the fermentation process, which is obtained by the separation from the ethanol through the filtration process. Nonetheless, spent less are the residues that are obtained from the rectifier column [20]. Among these wastewaters, spent wash is considered the major production from the ethanol distillery, and it is also known as vinesses, stillage, and distiller spent wash water (DSW) [21]. The production rate and properties of DSW are largely dependent upon the feedstock, fermentation practice and unit operations that are involved in the processing of the molasses and ethanol [22].

The effects of untreated effluents have been known for a long period. Especially, discharge of DWS can block the light and result a reduction in the availability of the oxygen and the survival of the aquatic life [23]. The disposal of DSW also can cause turbidity in the water bodies, which can decrease the light penetration and diminish the biological activities [24]. Additionally, DSW is a source of P, nitrates and sulfates, which can also cause eutrophication in the water bodies [25]. Moreover, leaching of the DWS into the groundwater can cause severe environmental contaminations [26]. The uncontrolled and un-treated discharge of the DSW into the water bodies can also create an unpleasant smell due to the presence of the pollutants [27]. The drinking of the DWS by the animals can result in a poor growth and an increase in their mortality [28]. Thus, DWS can pose a serious threat to the environment and living organisms. Therefore, this problem should properly manage to reduce its impacts on the environmental quality.

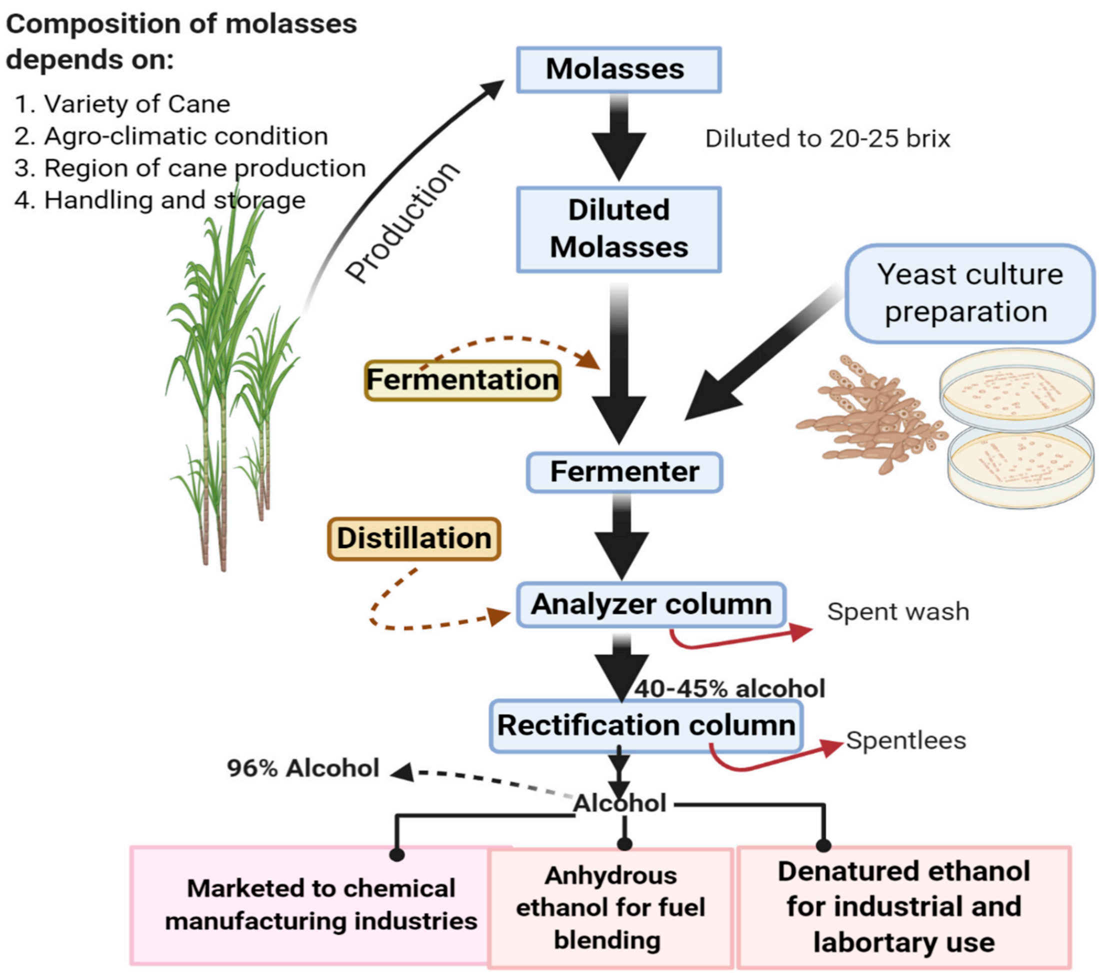

Figure 1. The involved process of the ethanol manufacturing in the sugar industry.

4. Properties of DSW

DWS is considered as the most complex and problematic effluent owing to the low pH and high COD (80,000–160,000 mg/L), temperature, ash contents [15,29,30]. Thus, DWS is considered as a difficult product to be disposed owing to the presence of the pollutants in such product [19]. Moreover, the presence of high OM % can cause the dark brown color to the DSW. The colorization in the DWS can be caused through different substances such as melanoidins, phenolics and furfurals that are used in the processing [31]. Among these color-causing substances; melanoidin is considered as the major cause of the dark brownish color of the DWS [32]. The molasses-based ethanol DSW is the main source of the melanoidins in the wastewater [33]. It was estimated that the molecular weight of the meanoidins ranged between 5000 and 40,000 Da and accounts about 2% of the total DWS [34]. The molasses DWS has many composition resemblances with sugar industry wastewater, however, DWS is considered to be high strength wastewater. The different beneficial properties of DWS are presented in Table 1.

Table 1. Characteristics of distillery spent wash (DSW).

Characteristic	Value	Characteristic	Value
pH	3.9–4.3	Copper	0.4–2.1
EC (dS/m)	30.5–45.2	Manganese	4.6–5.1
Nitrogen	1660–4200	Sodium	492–670
Phosphorous	225–3038	Iron	6.3–7.5
Potassium	9600–17,475	Gibberellic acid	3246–4943
Calcium	2050–7000	Indole acetic acid	25–61
Magnesium	1715–2100	Cadmium	0.005–0.036
Sodium	492–670	Lead	0.16–0.19-
Sulphate	3240–3425	Chromium	0.05–0.067
Zinc	3.5–10.4	Nickel	0.09–0.14
Chemical oxygen demand	104,000–134,400	Biological oxygen demand	46,100–96,000

All the values are given mg L^{-1} except EC [5,35,36]

5. Traditional Sugarcane Industrial Wastewater Management

The ultimate goal of the wastewater is to reduce its impacts on the environment and the living organisms. Thus, the treatment of the wastewater is very imperious to reduce its impacts on the environment. For different purposes, the treatment of the wastewater generally comprises physical, chemical and biological methods to remove the pollutants for ensuring the reuse of the wastewater. Therefore, to achieve the desired level of pollutant removal, the wastewater treatments can be divided into different systems, i.e., preliminary, primary, secondary, and tertiary treatments. The primary treatment involves the removal of solids, oil, and fats, while secondary treatment involves the removal of OM and nutrients, and tertiary treatments are generally referred as the polishing stage [37].

The most common practices being used in the management of DSW are the fert-irrigation, bio-composting, and incineration. The fert-irrigation involves the use of soil medium, and the disposal of the waste in the soil is becoming a common technique [38]. The application of wastewater for agriculture can be a viable method of disposal, and it can sustain the productivity in areas facing limited water availability [39]. Moreover, the use of DSW can reduce the application of fertilizers and irrigation. However, improper disposal of DSW can be hazardous for soils and vegetation [40] owing to the presence of toxic substances [41].

The condensation of DWS by evaporation is another important alternative option for the use of such residue. In this technique, DWS can be burned in boilers to generate energy, and the condensate removed by the evaporation can be treated and reused through the factory. Moreover, the obtained product as a result of this process can be used to prepare the animal feed [42]. This treatment can reduce the transportation caste and increase the radius of the DSW application as well as can make fert-irrigation unfeasible. Nonetheless, this technology is associated with many problems including the quick incrustation of evaporators, energy-intensive processing, spontaneous crystallization and higher energy demands [42].

Bio-composting (BC) is another imperious management practice being used in the sugar industry for the management of wastewater. Bio-composting involves the preparation of organic manure via mixing the press-mud and DSW [43]. The conversion of sugar industry waste into organic manures is considered a good practice to manage the waste with the additional benefits of reducing the application of inorganic fertilizers. Moreover, DSW can be subjected to anaerobic digestion to reduce the pollutants, BOD and COD before mixing with press-mud to produce BC [44,45]. Additionally, it is very difficult to manage the huge quantity of DSW through BC, since it is a very slow process and can take 15 days for a single treatment.

6. Effect of DSW on Crops

6.1. Crop Germination and Stand Establishment

The first and foremost phenomena of the agriculture production are the optimal germination and well stand establishment. The application of DSW as an irrigation source substantially affects the seed germination and the stand establishment, but it depends on the concentration of DSW (Table 2). A high concentration of DSW can decrease the seed germination due to the presence of the high salt concentrations which can cause high osmotic pressure. Conversely, the low concentration of DSW can improve the seed germination due to the low osmotic pressure [46]. On the other hand, the application of diluted DSW can improve the seed germination and seedling growth due to the presence of the optimal level of the plant nutrients such as N, P, and K [6]. At high concentration, DSW becomes deleterious for seed germination and seedling growth due to the high concentration of heavy metals such as Cu, Cd, Zn, Fe, Ni, Mn, and Pb [47]. DSW application into the soil can enhance availability of plant nutrients including N, P, and K. Consequently, the use of DWS can enrich the soil fertility and subsequent plant growth. The application of DSW can improve the soil enzymatic activities, which in turn improve plant growth and yield of crops [48]. However, high concentration of DWS can reduce the plant growth owing to the presence of high BOD content which can lead to O_2 depletion and increase in CO_2 accumulation in soil [48].

DWS can also reduce the sprouting of bud owing to the anaerobic conditions produced as a result of high BOD and COD contents that may be ascribed to the nutritional imbalance and reduction in the availability of nutrients. This can be due to the increased soil osmotic potential as a result of the higher concentration of DSW [6]. In legumes, the high concentration of DWS also adversely affect the nodules formation and root growth, however, the diluted DWS can resulting in a substantial increase in the nodules, rhizobium population and root hairs formation [49]. The low doses of DWS (50 m^3 ha^{-1}) were found to have no adverse impacts on the root growth, and were even found to have stimulatory effect on the crop growth [50,51]. The better crop growth as a result of diluted DWS application can be attributed to the manuring effect and the increase in the nutrients uptake [52]. DSW application at a lower rate (5 mL kg^{-1} soil) enhanced enzymatic activity and nutrient uptake, which results in a considerable increase in the growth traits and chlorophyll contents than the higher rates [6]. At high concentration of DSW (100 mL kg^{-1} soil), DSW can have inhibitory impacts on the mitotic and metabolic activities which results in a reduction in the growth and quality of crops [6]. Thus, it is concluded that DSW can improve the germination and stand establishment by favoring the nutrient uptake and microbial activities. However, it depends on the concentration, and the wise concentration of DSW should be applied to the crops for getting the desirable benefits.

6.2. Effect of DSW on Photosynthesis

The diluted/less concentrated application of waste can reduce the membrane injury compared to the highly concentrated one [53]. The application of concentrated effluent increased the uptake of toxic metals, and reduced the water uptake which in turn can cause the membrane injury [54]. The application of a lower concentration of DSW increases the chlorophyll contents (Table 2) owing to an increase in the synthesis of chlorophyll compared to the higher concentration of DSW [5,55]. However, the higher concentration of DSW reduced chlorophyll contents due to the reduction of the nutrient availability [5] and the formation of the chlorophyllase enzyme which is considered to be responsible for the degradation of chlorophyll contents [56]. The application of lower doses of DWS improved photosynthetic activities (Table 2), stomatal opening and rate of transpiration owing to the improvement of nutrients uptake and soil quality compared to the higher doses of DSW [57]. In another study, Yadana et al. [58] noted that an adequate nutrient supply at low concentration of DWS significantly improved photosynthetic efficiency and subsequent growth and yield of crops [30].

The application of diluted DSW can lead to a significant improvement in the photosynthesis (Table 2) due to the better nutrient uptake, chlorophyll synthesis, and reduced uptake of toxic metals and inorganic pollutants [59,60]. The increase in uptake of heavy metals at high concentrations of DSW can also reduce the metabolic and enzymatic activities [61,62]. Likewise, increasing the metals uptake at the high concentration of DSW caused a reduction in the chlorophyll synthesis by damaging the photosynthetic apparatus [63,64] which can lead to a significant reduction in photosynthetic activity, assimilates production and final production of crops. To summarize, the optimized dose of DSW can significantly enhance photosynthesis by improving the chlorophyll synthesis and nutrients uptake.

Table 2. Effect of DSW on plant growth, development and different physiological processes.

Recommended Practices	Crop	Effects	References
200 m^3 ha^{-1} (liquid DSW)	Groundnut (*Arachis hypogaea* L.)	Increased the protein and chlorophyll contents seed yield and methionine and cysteine contents	[65]
10% (*w*/*w*) (iquid DSW)	green gram (*Vigna radiate* L.)	Increased biomass production, photosynthetic pigments, and protein and starch contents.	[46]
1:3 (DWS:Water) (liquid DSW)	Amaranth (*Amaranthus viridis* L.)	Increased the grain protein, carbohydrates, zinc and iron.	[66]
1:3 (DWS:Water) (iquid DSW)	Leafy Vegetables	Improved the growth, yield and nutrients uptake (Ca, Mg, Fe, Zn etc.)	[67]
100 mL kg^{-1} soil (liquid DSW)	Sugarcane (*Saccharum officinarum* L.)	Improved the bud sprouting, root length, chlorophyll a and b and activities of catalase.	[6]
25% NPK+75 DSW (iquid DSW)	Sugarcane (*Saccharum officinarum* L.)	Increase in cane and sugar yield, and uptake of N, P and K.	[68]
10% DWS + 2/3rd NP	Sugarcane (*Saccharum officinarum* L.)	DSW improved root and shoot length, tillers, shoot weight and seedling vigor index.	[69]

6.3. Effect of DSW on Anti-Oxidant Activities

Stress conditions lead to the production of reactive oxygen species (ROS) which has negative impacts on plant molecules including, protein, lipids and DNA. The high concentration (100 mL kg^{-1} soil) of DSW reduced the activities of anti-oxidant and lead to a significant increase in the production of ROS [6]. However, the low concentration of DSW application (5 mL kg^{-1} soil) improved the activities of catalase (CAT) and results in a significant reduction in ROS and improvement in plant growth [6]. In another study, Baghel [70] noted that increasing concentration of DSW increased the CAT activity in pea plants. Moreover, other authors also found an increase in peroxidase (POD) activity at different levels of DSW application which showed the general response of the different nutrient stress [65,70]. DSW can also affect the concentration of the soluble proteins (SP); as Jain and Srivastava [6] found maximum SP in tissues of plants grown in untreated plots with DSW, whereas the lowest SP were noted at highest concentration (100 mL kg^{-1} soil) of DSW application [6]. Therefore, the optimal dose of DSW can improve the activities of CAT and POD, which in turn can scavenge the ROS. However, there remains missing information about the effect of DSW on the superoxide dismutase (SOD) and other non-enzymatic anti-oxidants. Thus, future research should address these questions.

6.4. Effect of DSW on Yield and Quality

The crop improvement is usually measured in terms of quality and quantity parameters; in DSW, it is about its nutritional value and optimization of soil properties. Gemtos et al. [71] reported that DSW not only substitutes N requirements of the wheat crop but also significantly increases the yield over the farmer practices. The use of DSW remarkably increased seed germination, subsequent growth and yield of dry land crops [72]. Likewise, the application of DSW improved the fruit weight and the size of vegetable crops [73]. In addition, the application of DSW combined with rock phosphate increased the uptake of P by 30% in sorghum crop compared to the individual use of the rock phosphate [74]. In India, Rath et al. [5], reported that the application of 50% diluted DSW improved the growth attributes and chlorophyll contents in sugarcane crops compared with the farmers′ practice. Also, the application of diluted DSW improved the productivity and nutrients uptake in leafy and root vegetables [75], and enhanced the growth, yield, and nutrient contents in the condiments [73], top vegetables, and medicinal plants [76]. Furthermore, DSW in combination with bio-compost significantly improved protein, grain oil, and grain NPK contents [77].

DSW application can considerably improve the yield traits, yield and quality of crops owing to the improvement in the availability of nutrients, microbial activities and OM which in turn improve the overall crop productivity [78–80]. Moreover, DSW can enhance photosynthetic activity which can increase dry matter productivity [81]. However, the high concentration of DSW reduced grain production and quality, possibly due to the reduction in the photosynthetic activities and increase in the availability of the salts and toxic metals [82]. Other researchers noticed that DSW application enhanced the sucrose contents, which was reflected in terms of the improvement in the juice sucrose contents [83]. Moreover, the DSW application can improve the yield of commercial sugarcane due to the improved yield and sucrose contents [84]. Therefore, the improvement in the crop yield and quality by DSW can be associated with the improved nutrient uptake, germination, stand establishment, OM, photosynthetic, and microbial activities.

7. Effect of DSW on Soil Health

7.1. Effect of DSW on Soil Enzymatic Activities

The application of DSW significantly improved the enzymatic activity compared to the control treatment [85], which can cause a significant improvement in the crop performance. The application of DSW significantly improved the phosphatase activity at various stages of crop growth [48,86]. Dehydrogenase enzyme is considered as an imperious indicator for soil biological activities [87]. For example, DWS application significantly improved the activity of dehydrogenase. However, the activity of this enzyme significantly varied with different application of DSW [48]. Dehydrogenase plays a crucial role in the oxidation of OM at initial stages by transferring hydrogen and electrons from substrates to acceptors. The increase in dehydrogenase activity with DWS application indicates the building of OM, which can enhance the microbial activity [88]. A positive association between dehydrogenase activity and OM has been reported by Adak et al. [89]. Also, DWS application results in an increase in the urease activity. Such an increase in the activity of dehydrogenase can be due to the increase in OM, nutrients, and microbial biomass [90]. Similarly, the increased microbial biomass due to the addition of DSW, can enhance the phosphatase activity [91]. Moreover, Dinesh et al. [92] concluded that the addition of organic substances caused an increment in the microbial activity, which favors the enzymes activity in the soil. Therefore, DSW can improve the enzymatic activities owing to the addition of OM and increased microbial activities.

7.2. Effect of DWS on Soil Organic Carbon

The application of DSW can cause a significant increase the organic carbon (OC) in the soil, which in turn improve the overall soil fertility status. The high OC and nutrients present in DSW serve as an energy source for the growth, enzymatic processes and multiplication of microbes. DSW application at the rate of 156 m^3 ha^{-1} resulted in a maximum microbial biomass carbon (MBC) (280 lg g^{-1}) compared with untreated soil (127 lg MBC g^{-1}) [93]. DSW application increases the OM and nutrients, and consequently leads to an increase in the microbial biomass [93] which, therefore, significantly increased in soil carbon. The microbial quotient (MQ) is considered as a sensitive indicator for the soil OM quality. High MQ means that the soil OM can sustain a large microbial population, whilst low MQ indicates that OC is less palatable and can accumulate a low microbial population. OC present in soluble form in DSW [94] that sustains and enhance the microbial population and their activity, which therefore, increase MQ. Soil respiration, as shown by CO_2 evaluation and consumption of oxygen, is also considered an important indicator for the microbial activity. An increase in the microbial respiration with increasing the DSW rate has been observed [93]. Similarly, Deshpande et al. [95] observed an increase in the microbial respiration with increasing the DSW owing to the building up of OM. They also noticed that the application of DSW appreciably increased the soil OC and OM contents. To summarize, DSW favors microbial activities, which in turn increases the mineralization of the organic substances, and therefore, increases the soil OC.

7.3. Effect of DWS on Soil Microbes

Soil microbes play an imperious role in the nutrient cycling and OM stabilization [96]. Generally, the microbial population significantly increased at the earlier stages of crop growth with the application of DSW. However, the microbial population decreased over time owing to the degradation of OM and nutrients. The sustainability of the soil health largely depends on the efficient microbial activities and their population [97]. DSW appears to improve the microbial population and microbial growth. Moreover, other authors noted significant improvements in the microbial activity in the soil treated with DSW and cultivated with sugarcane, groundnut and sunflower [48,85,95,98]. Most of the soil bacteria, fungi and actinomycetes are heterotrophic, and they require OC for energy, and high OC in DSW, along with sugar and protein enhance the microbial population [99]. In conclusion, DSW application into the soil can increase the soil OM and OC which can serve as an energy substrate for microbes, and therefore can improve the microbial population and their activities.

7.4. Effect of DSW on Nutrient Uptake

The DSW contains valuable macro- and micronutrients (Table 3), therefore, it can be valuable fertilizers for crop production [73]. The diluted DSW markedly increased the uptake of Mn, Fe, Cu, and Zn by maize plants as compared to untreated plots. However, the maximum uptake of these nutrients was recorded with diluted DSW as compared to the concentrated one [100]. The diluted DSW improved the nutrients uptake in mint leaf, vegetables, pulses, and root vegetables [75,101]. The application of DSW in combination with the phosphorus at a ratio of 1:20 substantially increased the uptake of P by 30% than the sole application of P [74]. In another study, the application of DSW remarkably improved the growth and yield attributes of sugarcane as well as increased nutrient uptake compared to the sole application of the recommended fertilization [5].

The application of DSW significantly increased the micro-nutrients (i.e., Fe, Cu, Zn) uptake due to the presence of high OM and nutrients in DSW (Table 3). However, the magnitude of the uptake increased after application of DSW compared to after harvesting owing to the nutrient uptake by the crop [102–104]. Similarly, DSW increased the uptake of K^+, Ca^{2+}, and Mg^{2+} owing to the presence of a high percent of these nutrients in DSW [95]. On the other hand, application of DSW resulted in a reduction in the Na^+ contents owing to the presence of the high Ca^2+ that can replace the Na^+ in soil [105,106]. Application of DSW also increased the concentration of HCO^{3-}, Cl^- and SO_4 in soil due to the presence of a high amount of these ions in DSW [107]. DSW also increased the soil P content in soil due the presence of P in this product. Additionally, the decomposition of DSW can produce some organic acids that can reduce P fixation and increase the availability P in soil via the solubilization of the resident phosphorus [72]. Similarly, the application of DSW substantially improved the N uptake with the increased rate of its application [103,108,109].

Thus, the increment of the nutrient uptake after the application of DSW can be due to the improved soil characteristics and the enhanced enzymatic activities.

Table 3. Effect of sugarcane distillery spent wash on soil characteristics.

Crops	Treatment	Effects	Reference
Wheat (*Triticum aestivum* L.) and soybean (*Glycine max*)	2.5 cm DSW (liquid DSW)	DSW significantly increased the SHC, field capacity, and reduced the bulk density	[110]
Black gram (*Vigna mungo* L.) and cow pea (*Vigna unguiculata* L.)	33% DSW (liquid DSW)	DSW application significantly increased nutrient uptake	[111]
Wheat (*Triticum aestivum* L.) and soybean (*Glycine max*)	2.5 cm DSW (liquid DSW)	DSW improved the soil organic carbon and aggregate stability	[112]
Okra (*Abelmoschus esculentus* L.)	100% DSW (liquid DSW)	DSW increased the moisture contents, EC, K, Ca^{+2}, Mg^{2+} and available P and total nitrogen.	[38]
Sesame (*Sesamum indicum* L.)	75% DSW (liquid DSW)	DSW increased the microbial and fungal population and increased activities of dehydrogenase and Phosphatase	[113]
Sugarcane (*Saccharum officinarum* L.)	10% DSW: (liquid DSW)	Increased cane yield, soil organic matter, soil NPK contents	[114]
Tomato (*Solanum lycopersicum* L.)	10% DSW (liquid DSW)	DSW application decreased the pH and increased the EC, N, P, K, Fe, Zn, Cu, Mn plant height and tomato yield	[115]
Sugarcane (*Saccharum officinarum* L.)	DSW: Water (1:10) (liquid DSW)	DSW increased the soil carbon and N, P and K contents	[116]
Finger millet (*Eleusine coracanaand* L.) maize (*Zea mays* L.)	100 m^3 ha^{-1} (liquid DSW)	DSW enhanced the soil pH, K, and yield of both maize and finger millet.	[117]
Wheat (*Triticum aestivum* L.)	25% DWS (liquid DSW)	DSW increased the, N, P and K uptakes and yield, grain weight and yield	[118]
Sesame (*Sesamum indicum* L.)	100% DSW (liquid DSW)	DSW increased the microbial, fungal and actinomycetes population and activities of phosphatase, dehydregenase and urease	[119]
Sugarcane *(saccharum officinarum* L.)	160 t ha^{-1} (liquid DSW)	DWS increased the N and P uptake, sugar yield and juice quality	[120]
Sunflower *(Helianthus annuus* L.)	180 m^3 ha^{-1} (liquid DSW)	DSW application increased Ca^{+2}, Mg^{2+}, and K^+ and reduced the exchangeable sodium	[121]

7.5. Effect of DSW on Soil Quality

DSW is a rich source of macro and micronutrients, and it can be used as the prime source of fertilizer for agriculture. Conversely, the indiscriminate disposal of this waste can pose some problems to the soil health and environmental quality. Globally, DSW has been characterized as an important source to improve the soil properties such as nutrient availability, bulk density, soil porosity, nutrient and water holding capacity, hydraulic conductivity, and microbial activities (Table 3) as well as the crop growth and development [122]. The application of DSW improved the microbial population and their activities, which increased the decomposition of the organic matter and thereby increased the availability of the carbohydrates and humified substances [123]. In addition, the use of DSW increased the soil aggregate stability compared with the application of farmyard manure and inorganic fertilizers [110]. In China, it was reported that the application of

DSW improved the soil macro-aggregates with more biodegradable C and N compared with the farmer practices. Such an improvement in the soil traits results in a substantial improvement in the soil fertility [124]. DSW increased the OM content, soil porosity and evenly improved the soil water holding capacity [125].

Application of DSW also increased the saturated hydraulic conductivity (SHC) and decreased the bulk density (BD) due to presence of high organic loads and Ca^{2+} that can reduce the soil BD and increase SHC [109,110]. Furthermore, the application of DSW improved soil aggregation stability, which in turn improved soil porosity and SHC [110]. The presence of high OC in the DSW can enhance the release of organic acid that can cause a reduction in soil pH [104,126]. Moreover, the application of high DSW doses caused an increment in the soil EC owing to the high content of soluble salts in DSW [95,103].

DSW can lead to a significant increase in the CEC compared to untreated soil. Similarly, Shinde [127] noticed an appreciable increase in CEC with the application of DSW (180 m^3 ha^{-1}) compared to the control treatment. The application of DWS improved the CEC as a result of the high BOD [95]. The application of DSW also reduced the exchangeable sodium percentage (ESP) in soil owing to the increase in the soil CEC and reduction in exchangeable Na^+ that can be replaced by the released Ca^{2+} from the DSW [95,126].

8. DWS a Pollutant

The utilization of DSW in agriculture is an essential preservation hone. However, its use has been tested owing to the presence of the high organic loads [128]. The obstinate use of the higher quality DSW promptly increased the soil N and K contents [129], moreover, DSW also enhanced the soil aggregation, which in turn improve the water infiltration and soil quality. Recently the impact of untreated and highly concentrated DSW on the soil properties was investigated. The authors noticed that the concentrated DSW induces soil salinization due to the presence of the high salts quantity [130]. In another study, authors found that deposited DSW had negative impacts on the water quality as well as the authors recommended that the negative effects of DSW can be reduced by the biological treatments [131].

Lyra et al. [129] examined the soil quality in the areas where sugarcane was fertigated with DSW (300 m^3 ha^{-1}). They found that application of DSW affected the water quality regardless of soil types. Similarly, Ramalho et al. [132] studied the impact of DSW on the soil properties. They noticed no significant increase in the heavy metals in the soil treated with DSW. Therefore, Ramalho et al. [132] stated that a little danger of the soil pollution can occur with the application of DSW. The impact of different DSW rates on the soil properties was investigated, and it was noticed that the cation fixation in the leachates was less than those found in DSW, indicating a high retention in soil [133]. Brito et al. [133] assessed the physicochemical characteristics of soils treated with DSW for 30–60 days. They noticed that there was no environmental problem, and reported that the danger of ground water contamination was very low. According to the above-mentioned studies, there is no agreement related to the contamination for the environment, water and soil as a result of DSW application. The two primary lines of thought show that on one side the dangerous impacts of DSW for the surface and groundwater, whilst on the other side claims that judicious use of DSW does not have any ecological danger. Therefore, it must be emphasized that relying upon the DSW application can be a toxic or a valuable soil conditioner.

9. Implications of DWS for Agriculture and Water Quality

The use of DSW in the agriculture and its corresponding impacts on the surface and groundwater quality depends on the soil properties (slope, depth, clay contents, and SHC) and DSW properties (composition, rate, time, and depth of groundwater) [134]. Higher EC, Cl-, sulphates and melanoidine as coloring agents are the main components in DSW for causing the pollution [135]. Studies conducted in many countries indicated that the poor management of DSW can lead to the water pollution [136]. The indiscriminate DSW application in agriculture to those areas with a shallow water table (<15 mm) linked with the sandy soils, have the high infiltration rate is highly prone to the pollution, and the application of DSW cannot be recommended in those areas. Nonetheless, continuous DSW application (600 m^3/ha) did not cause any groundwater pollution [137]. The generalized rates of DSW in agriculture are generally not beyond the 500 m^3/ha, and such rate can cause a low probability for groundwater pollution due to the absorptivity and microbial induced oxidation of DSW [138,139]. In Brazil, the continuous use of DSW at 300 m^3/ha in clay loam soil for fifteen years did not change the groundwater quality [138]. However, the nitrates and other pollutants were reduced at the waterfront with depth, where the rate of anions mobility in soils was very low with the application of DSW [138].

The application of DSW in the rainy seasons can increase the water pollution owing to the rapid runoff and leaching in the areas with sloppy lands, therefore, DSW is not recommended for these areas [140]. In many counties, industrial water is stored in lagoons that can leach out into the water tables. So, the proper structural modification must be opted to overcome this problem when DSW is applied [28]. The water quality should be continuously checked, and four permanent pores of 15 m length must be made per 10 hectares. DSW must be treated up to BOD of 100 mg/L and total dissolved solids (TDS) of 2100 mg/L for its use as ferti-gation. Furthermore, the DSW application as compost, ferti-gation and land application should not be applied in the rainy seasons [141]. The approach of groundwater monitoring, optimized time and space of DSW application, mixing with high quality water and judicious use of DSW in agriculture must be considered to ensure the better quality of the groundwater. Thus, the optimum timing and space in the judicious use of DSW into agriculture is friendly for the environment, and is an important component for improving the environmental quality.

10. Health Risk Associated with Application of DSW

Potential toxic elements (PTE) are substantially increased in grains and straw with increasing the concentration of DSW which can be due to the increase in the availability of the heavy metal [80]. Moreover, the reduction in the physiological activities at the higher concentrations of DSW can be due to the increase in metals accumulation in the above-ground plant parts and reduction in the transpiration and metal exclusion [142,143]. The concentration of PTE is considered to be high in the straw than the grains owing to the fact that straw is the second plant organ comes in contact with metals after root. The application of an optimized dose of DSW can improve the production and soil health, and reduce the health risks. Likewise, under the application of 5% DSW, all PTE in the grains were within the limits of WHO and the permissible limit (PL), as well as the concentration of PTE was also within the PL of PTE in animal fodder and livestock feeds as recommended by America and Russia [80]. Therefore, the application of 5% DSW ensures the adequate availability of micro-nutrients, which can fulfill the nutrient, needs [80].

The application of an optimized dose of DSW can reduce the chances of health risks in humans according to the health risk index (HRI). Likewise, Naveed et al., [80] noted that all PTE were less than 1 with the application of 5% DSW. However, the concentration of cadmium, manganese (Mn) and arsenic (As) was greater than 1 with the higher concentration (above 5%) of DSW. These authors also suggested that HRI was based on the daily intake of the metals (DIM) and oral dose reference (RfD) for each metal as suggested by the different authorities/agencies. Additionally, Naveed et al. [80] also suggested that daily dietary intake of PTE in grains produced from the 5% DSW for children and adult consumption was within the safe limit as suggested by [144]. Thus, optimizing the dose of DWS application would be safer for humans, while the high concentration of DSW can induce health risks for humans and animals.

11. Concluding Remarks and Future Prospects

Recycling of organic wastes can result in an increase in the soil OM and lead to the significant improvement in the soil productivity and fertility. DSW is an imperative source of macro-nutrients (i.e., N, P, K, Ca, and S) and micronutrients (Cu, Fe, Zn and Mn). The application of DSW improves the seed germination depending on its concentration. For instance, high concentration of DSW can reduce the seed germination owing to the presence of the high quantity of the soluble salts. Moreover, the liquid DSW can improve the plants growth, yield, and quality due to the increase in the nutrient availability, photosynthetic activities, anti-oxidants activities, and improvement in the soil fertility status. However, the high concentration of DSW can decrease the plant growth, and yield due to the increased BOD, COD and salts availability. Therefore, an optimized dose of DSW should be applied to the crops for ensuring the better germination and subsequent growth and development. Additionally, liquid DSW can improve the soil organic carbon, microbial and enzymatic activities, nutrient uptake, SHC, and CEC, which in turn can improve the overall crop growth, yield and quality.

Liquid DSW also contains a significant amount of soluble salts and sometimes toxic metals that can have adverse impacts on the soil quality. The disposal of DSW can directly pose environmental problems. However, the bio-composting of DSW to make compost is an important strategy for reducing its impact on the environment and for using it as a valuable source in the agriculture. The value of DSW as a nutrient source is well recognized, however, the sustainable agronomic packages still have to develop to improve the crop production and soil health without any adverse impacts on the environment. There is a need to develop the dilution at which DSW can be used in the irrigation as a nutrient source without any adverse effect on the soil health and crop performance. When the wise strategies would be available to the farming community, they would accept the use of the diluted DSW which would reduce the fertilizer application and increase the water availability for the agriculture.

However, many questions are still there and need to be addressed. The role of DSW in improving soil quality and crop yields is well documented. However, the effect of DSW on plant physiological aspects is not addressed. Likewise, the application of DWS can improve the photosynthesis however, the mechanisms related to the increase in the photosynthesis as a result of DSW application are poorly understood. Thus, future research should focus on the mechanism lying behind the increase in the photosynthesis as a result of DSW application. Plant water relations are an important physiological component, which fundamentally affect the photosynthetic efficiency and overall plant performance. No study was conducted about the effects of DSW on the plant water relations. Therefore, future research should be aimed to explore the role of DSW in plant water relations. There is also missing information about the role of DSW in the osmolyte accumulation and hormonal cross talk. Thus, future research should be amid to underpin the effect of DSW on osmolyte accumulation, hormonal cross-talk in order to enrich knowledge about the role of DSW in improving crop performance. Moreover, the effect of DSW on the activities of anti-oxidants is not fully explored, and futuristic research must be aimed to explore the effects of DSW on activities of both enzymatic and non-enzymatic antioxidants.

The information related to the application of DSW on the soil health and plant growth under different stresses (heat, drought, salinity) is completely missing. So, future research should also consider the use of DSW under different stresses to explore its mechanism in improving growth, soil health, and stress tolerance to enrich the knowledge about the DSW as an agricultural input. The un-judicious use of DSW can also increase PTE in food and feed crops, and can induce health risks to humans and animals. Thus, a wide range of studies should be conducted in different cropping systems to optimize the doses of DSW for different crops to improve the productivity and reduce the impacts on the environment soil and human health.

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Abbreviations

BC: bio-composting, BD: bulk density, BOD: biological oxygen demand, CAT: catalase, COD: chemical oxygen demand, CEC: cation exchange capacity, CCSY: commercial cane sugar yield, DSW: Distillery spent wash, DIM: daily intake of metals, ESP: exchangeable sodium percentage, HRI: health risk index, MBC: microbial biomass carbon, MQ: microbial quotient, OM: organic matter, NPK: nitrogen, phosphorus and potassium, POD: peroxidase, PL: permissible limit, PTE: potential toxic elements, RfD: oral dose reference, ROS: reactive oxygen species, SHC: saturated hydraulic conductivity, SOD: superoxide dismutase, TDS: total dissolved solids, WHO: world health organization, USEPA: United States environmental protection agency.

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