



# **Composting: A Low-cost Biotechnological Approach to Ameliorating Macrophyte Nuisance in Fresh Waters**

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. Author OAU designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors GOA and HOS managed the analyses of the study. Author HOS managed the literature searches. All authors read and approved the final manuscript.*

## **Article Information**

DOI: 10.9734/JAERI/2021/v22i330191

### Editor(s):

- (1) Dr. Md. Torequl Islam, Federal University of Piauí, Brazil.  
(2) Dr. Daniele De Wrachien, State University of Milan, Italy.

### Reviewers:

- (1) Marcel Bianchessi da Cunha Santino, Universidade Federal de São Carlos, Brazil.  
(2) V. Murugesu, Anna University, India.

Complete Peer review History: <http://www.sdiarticle4.com/review-history/68979>

**Review Article**

**Received 05 April 2021**  
**Accepted 10 June 2021**  
**Published 14 June 2021**

## **ABSTRACT**

Water Hyacinth (*Eichhornia crassipes*), an aquatic macrophyte, is a resource that has attracted a lot of interest in recent times. The physicochemical constituents of *Eichhornia crassipes* have been reported in some literature to constitute high carbon, nitrogen, phosphorus, potassium including other important micro and macronutrient like potassium and zinc. These findings by scientists informed its utilization in the assemblage of animal feed, bio-energy generation, pharmaceutical industries, and biofilters. The bioconversions of this problematic plant to various products (compost, biochar, and digestate) are green inexpensive options to be considered for use in the restoration of hydrocarbon polluted sites is reviewed in the paper. In addition to crude oil pollution clean-ups, compost improves soil fertility and also increases its organic matter content. This article also shall review composting, Water Hyacinth compost applications in remediation, remediation monitoring parameters, limitations of remediation by composting technology, and the way forward.

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**Keywords:** Water hyacinth; bioconversion; compost; bio-char; bioremediation.

## 1. INTRODUCTION

Compelled by global economic growth and development, bioconversions of agricultural, industrial and aquatic wastes into a useful value-added product have steadily increased. Recently scientists have shifted attention to investigating aquatic macrophytes as an alternative resource to be employed to solve societal problems. Water Hyacinth, which is a renewable resource, can cause menace by its invasion of freshwater bodies [1,2]. This annexation of the tropical marine ecological system has called for urgent attention. On the other hand, global food security and agricultural sustainability are being threatened as a consequence of the activities of human beings on earth. As a result, possibilities of synthesizing green fertilizers from *Eichhornia crassipes* is being considered to ameliorate the impact of crude oil exploration, oil drillings and refining activities, pipeline sabotage, and artisanal refinery activities in Nigeria with resultant leaks of hydrocarbon into the environment that has caused the loss of biodiversity, vegetation, coastal and agricultural land. These actions have adversely deprived arable land of nitrogenous and phosphate elements which are considered as 'limiting nutrients' based on Liebig's Law of the Minimum. In Sub-Saharan Africa for example, depletion of soil nutrients caused by these disruptions in the ecosystems has resulted in a drastic drop in agricultural yield and significantly affecting society hence the need to embrace this green alternative of fertilizer production through composting.

*Eichhornia crassipes* known as Water Hyacinth (WH) is a renewable, ever invading [2,3], aquatic Nutri-resource that has caused so much havoc on our water bodies [4]. Its nuisance (waste) can be transformed using biological options into several useful products [5] like the organic compost biofertilizers, [6] biochar [7], and digestates in the slurry form generated during the anaerobic digestion process for biogas production for eco-recovery of nutrient-depleted arable lands. Interest in agricultural waste recycling and biomass conversions has risen in recent times. As a result, eco-friendly products are now introduced into the environment as soil amendments and fertilizer when they are disposed of Gao et al., [8]. Besides, the exploitation of macrophytes in aquatic ecosystems or products of its biotransformation

for use in various remedial applications such as biofiltration for odour and air pollution mitigations, phytoremediation, and rhizo-filtration for removal of chemical contaminant, toxins, metals, and dye from polluted lands and marine systems are well known [9]. However, researchers are yet to fully explore *Eichhornia crassipes* as a resource (waste) with immense potential and to consider it being recycled or converted back into agricultural or bioremediation systems as a value product. In this review, strategies for the *Eichhornia crassipes* bioconversion to be evaluated include-composting, and bio-charing [10], [5]. Compost as a product and composting as a remediation technique which is now both attractive and desiring are attributed to its environmental friendliness, cost-saving and economics [11], high biodegradation potential, technological feasibility [12,13] and ameliorating health, social, economic or environmental problems that are linked to the ways organic waste are managed in our environment [11]. In the process of composting, pathways that could be deployed are aerobic and anaerobic [14,15]. In the aerobic composting pathway, oxygen is supplied to microorganism for their growth and metabolism thereby breaking down compost organic material into carbon dioxide and water whereas, in the anaerobic composting pathway, microbes that carry out their metabolic activities in the absence of oxygen (anaerobes) are the main players in the transformation of organic materials with a resultant release of methane gas into the atmosphere [16]. Slurries from the anaerobic fermentation (composting) process are good products for bioremediation application as well as biochar products of its pyrolysis. The goal for embarking on composting operation is often to produce a nutrient stable biofertilizer for vegetal development and improvement of soil nutritional status [17]. Microbes or their enzymes perform a vital function in the composting process [18]. Composting can either be done with single biomass or augmented with bulking agents alongside other supplements such as effective microbes. To reduce nitrogen loss during composting process additives like ash from burnt materials like wood, organic or inorganic forms of fertilizers, fish or bone char, limes, worms, and different microbial strains (bacteria and fungi) are often added to it [19,20]. To improve composting process operation and result [21], its operating parameters affecting compost time, stability and maturity need to be enhanced [22]. In other words, successful optimization of composting

parameters such as operating temperatures, microbial inoculum concentration, turning frequencies, transformation time, percentage moisture content and Carbon-Nitrogen (C/N) ratio would shorten the composting time and increase products quality [23,24,25,26,8].

The objectives of this article are therefore to (i) review challenges encountered in composting and possible solutions (ii.) identify the various resource products of *Eichhornia crassipes* bioconversion (iii.) analyse the various application for compost in the remediation of hydrocarbon contaminated soil. (iv.) Suggest the present challenges of the compost remediation application and way forward.

## 2. WATER HYACINTH – AN OVERVIEW

*Eichhornia crassipes* is one of the popular nuisances causing aquatic macrophytes that proliferates rapidly but absorbs pollutants from marine environments [27]. Many botanists introduce Water hyacinth as the invasive and free-floating water plant Gopal [28]. It belongs to the family Pontederiaceae, originating from the continent of South America where it is indigenous to Brazil, the Amazon basin, and the Ecuadorian reg. The growth of *Eichhornia crassipes* on aquatic surfaces can reduce the penetration of sunlight into the water body. Considering that many photosynthetic organisms depend on sunlight, the reduction of sunlight leads to a decrease in photosynthetic activities which consequently have a negative ecological impact [29]. Most of the studies on water hyacinth have emanated from the Amazon and tropical areas probably due to the plant's abundance in these regions [30,31]. Klumpp et al. [31] described the ecology, habitat, and applications of *Eichhornia crassipes*. WH has also been reported to be among the most productive plants in the world [28] hence the reason for its known aggressive nature. The invasiveness of *Eichhornia crassipes* is enhanced by the physiology of its root system, which is mostly elongated and suspends in water. The root structure of the plant presents a suitable environment for the growth and metabolic function of aerobic (oxygen loving) microbes in several ecological systems such as sewage [28]. In non-native countries, that is, where its presence is newly established and having fewer competitors for growth, the proliferation rate often increases due to lack of competitors [32]. It is estimated that a water body, with a size ranging between 5 acres to 20

acres or example, should accommodate up to two million WH, which is roughly equivalent to 400 tons [33]. Water Hyacinth is regularly cited in literature to be among the hard-to-manage plants worldwide because it is difficult to control in open water bodies. Water Hyacinth (WH) can attain rapid growth of over 60kg/m<sup>2</sup> of an aquatic surface with a deleterious impact on economic sustainability [34]. Unsuccessful attempts at controlling invasive plants have resulted in the development of alternative use for them as a more sustainable management strategy [35]. Some of the widely reported use for water hyacinth include as biosorbent for removing toxic metals [36], animal and fish feed [37], compost [30], feedstock for biogas and bioethanol production [38], herbal medicine for treating diseases [39], bio pulping [40], a raw material for manufacturing paper [40], and agent for phytoremediation [41]. Studies of Rommens et al. [42] on *Eichhornia crassipes* impounded water revealed that nitrate and phosphate concentrations in a kilogram wet plant are about 1.13 mg and 0.39 mg respectively. However, seasonal variation, temperature fluctuations, density, and area of its water coverage have a significant impact on the rate of its nutrient uptake hence, the reason for variations in the plant's physicochemical composition in different tropical regions [43]. The mineral endowment of the *Eichhornia crassipes* suggests that it can be harnessed as a nutrient source for agricultural and bioremediation purposes. Fig. 1 show the image of the *Eichhornia crassipes* plant.

### 2.1 Agro-economic Consideration of *Eichhornia crassipes*

Due to man's constant utilization of land resources and activities on soils, its often degraded, leached, or weathered. These activities have made it deficient in its physicochemical properties such as Electrical conductivity (EC). Micro and Macronutrients, organic matter, and pH [44]. Agricultural output (quality and quantity) from this degraded soil have greatly affected especially in Sub Saharan Africa [45]. Application of suitable nutrient supplements/amendment to the soil while adopting sustainable land management proactive in other to improve, maintain or boost the physicochemical properties of the degraded soil would be achieved using composting strategies [46]. Aquatic macrophyte, The *Eichhornia crassipes* for example is a valuable nutri resource as it contains a high level of limiting nutrient (nitrogen, phosphorus, and potassium)

which are vital for plant growth and development [47,48] thereby significantly impacting positively on soil and the resultant crop yield [49,50]. Hence, in regions where land is degraded as a result of constant cultivation of limited arable land and has resulted in drop-in productivity are therefore required to apply Water Hyacinth based compost [51]. Inorganic fertilizers, due to their high cost, are not handy to several micro and small-scale farmers [52]. In addition, several health (Human and livestock) and environmental (soil and water pollutions) hazards have been associated with the increased use of chemical/ inorganic soil amendments [53,54,55]. This review, therefore, acmes the value of organic composts such as those produced from problematic aquatic macrophytes such as the

Water Hyacinths, In particular, this agroeconomic significance.

## 2.2 Socio-economic consideration of *Eichhornia crassipes*

It is an established fact that the impact of infestation as invasion of Water Hyacinth (WH) in fresh waters has negatively impacted both social and economic aspect of society [32]. These effects are evident in areas of fishing folk activities, resident community public health - malaria outbreak resulting from mosquito breeding-, electrical power supplies (cables and pipelines), maritime activities (cargo and war ships, navigators, boats, vessels), and water supply chains and lost sites for recreation and



Fig. 1. (A) Floating *E. crassipes*. (B) Bulb/Rhizome

Table 1. Physicochemical constituent of Dried WH

Parameters	Stem	Root	Leaves	F-stat
Nitrogen (%)	2.34±0.02 <sup>b</sup>	1.97±0.02 <sup>a</sup>	2.80±0.02 <sup>c</sup>	431.08
Phosphorus (%)	5.30±0.05 <sup>b</sup>	4.86±0.04 <sup>a</sup>	7.10±0.07 <sup>c</sup>	915.12
Potassium (%)	36.66±0.30 <sup>b</sup>	18.48±0.04 <sup>a</sup>	53.95±0.07 <sup>c</sup>	20378.998
TOC (%)	13.59±0.09 <sup>a</sup>	9.44±0.05 <sup>b</sup>	15.81±0.14 <sup>c</sup>	1324.77
TOM (%)	23.27±0.02 <sup>b</sup>	16.18±0.02 <sup>a</sup>	23.27±0.02 <sup>c</sup>	103264.15
Cellulose (wt.%)	10.21±0.04 <sup>a</sup>	19.56±0.03 <sup>c</sup>	15.29±0.05 <sup>b</sup>	14525.28
Lignin (wt.%)	4.79±0.12 <sup>a</sup>	10.96±0.02 <sup>b</sup>	8.63±0.02 <sup>c</sup>	1915.90
Hemicellulose (wt.%)	15.90±0.04 <sup>a</sup>	24.76±0.01 <sup>c</sup>	17.96±0.04 <sup>b</sup>	22056.52
Reducing Sugar (mg/L)	8.49±0.06 <sup>c</sup>	5.23±0.04 <sup>a</sup>	6.79±0.05 <sup>b</sup>	1003.14
Wax (wt.%)	11.51±0.03 <sup>b</sup>	9.74±0.03 <sup>a</sup>	15.09±0.01 <sup>c</sup>	16541.17
Total Carbohydrates (wt.%)	28.23±0.04 <sup>c</sup>	18.64±0.02 <sup>b</sup>	18.64±0.02 <sup>a</sup>	20863.73

Key: Data represents duplicate Mean± Standard Error; Superscripts reflect homogenous subsets, Columns with similar superscripts are significant at  $p < 0.05$  and otherwise are not significant at  $p > 0.05$

**Table 2. Physicochemical constituent of Fresh WH**

Parameters	Stem	Root	Leaves	F-stat
Nitrogen (%)	2.78±0.02 <sup>b</sup>	2.19±0.01 <sup>a</sup>	2.97±0.03 <sup>c</sup>	515.24
Phosphorus (%)	4.94±0.02 <sup>b</sup>	4.27±0.01 <sup>a</sup>	6.39±0.07 <sup>c</sup>	12810.55
Potassium (%)	31.96±0.02 <sup>b</sup>	17.52±0.02 <sup>a</sup>	51.77±0.04 <sup>c</sup>	479331.176
TOC (%)	10.54±0.01 <sup>b</sup>	8.74±0.03 <sup>a</sup>	12.88±0.01 <sup>c</sup>	10526.714
TOM (%)	18.11±0.11 <sup>a</sup>	14.85±0.05 <sup>a</sup>	12.49±9.50 <sup>a</sup>	0.265
Cellulose (wt.%)	8.97±0.03 <sup>a</sup>	13.89±0.02 <sup>c</sup>	11.85±0.04 <sup>b</sup>	7483.85
Lignin (wt.%)	3.55±0.03 <sup>a</sup>	7.25±0.03 <sup>a</sup>	7.46±1.53 <sup>a</sup>	6.243
Hemicellulose (wt.%)	12.82±0.04 <sup>a</sup>	20.60±0.17 <sup>b</sup>	13.92±0.07 <sup>c</sup>	1519.624
Reducing Sugar (mg/L)	9.70±0.01 <sup>c</sup>	6.20±0.03 <sup>a</sup>	8.04±0.03 <sup>b</sup>	5933.242
Wax (wt.%)	18.40±0.16 <sup>c</sup>	11.88±0.02 <sup>a</sup>	17.21±0.02 <sup>b</sup>	1477.741
Total Carbohydrates (wt.%)	31.49±0.02 <sup>c</sup>	25.16±0.03 <sup>b</sup>	19.59±0.02 <sup>a</sup>	69679.197

Key: Data represents duplicate Mean± Standard Error; Superscripts reflect homogenous subsets, Columns with similar superscripts are significant at  $p < 0.05$  and otherwise are not significant at  $p > 0.05$

spiritual activities [56]. Ultimately, livelihoods and economic development have significantly been affected by these concerns arising from these noxious weeds. Despite these socio-economic problems brought about by these alien macrophytes, there are also up-sides to it. *Eichhornia crassipes* has been reported to be a renewable resource in aspect of energy as in generations of bioenergy in form of biofuels (biogas, bio diesel, bio ethanol) due to its rich cellulose and hemicellulose constituent that are easily converted to bio-synthesizable sugars [32], as raw materials used for art and craft works as in, papers production, ropes, bags, basket and pups [57] or in livestock farming as in fish, duck and pig feeds [58,59], in pharmacy and Medicine as starter materials and nutraceuticals [60]. Additionally, alkaloid, phthalic, propanoic and phenylic compounds and derivatives extracted of *E. crassipes* have shown significant therapeutic activities [60] and also in water purification [61,62]. In order alleviate man from this nagging problems, composting biotechnology has proffered a cheap, energy saving solution. Application of biotechnology process of compost production is ancient but remains an innovative green-tech (GT) method of producing biofertilizers from *Eichhornia crassipes*. Its Phyto and physio chemical constitutes of the biomass (stem, leaf and root) has made it an excellent material for production of eco-safe *nutri-resource* used for either agriculture or remediation [63] purposes. Water Hyacinth is either utilized as a sole feedstock material for composting, in combination of other nutrient amendments such as bio-chars and peats for improved nutrient and stability [64,65,66] or co-composted with agricultural waste (animal and plants) as well as kitchen/domestic wastes to improve soil structure and enhanced soil moisture retention rate especially in area associated with drought [67].

### 3. COMPOSTING PROCESS

Composting is an oxygen-requiring process by which organic materials are broken down and transformed into a dark brown humus-like substance (organic fertilizer) as a result of microbial activities acting on the material while keeping condition supporting these activities (e.g. Moisture, temperature, pH, and proportions of nitrogen and carbon) optimized (See simple process flow in Fig. 2) [68,69]. It is expected that at the end of every composting process operation, a mature, nutrient-rich stables product would be obtained for use in soil physicochemical and biological property enhancement [70,71,72,73]. Compost application on degraded or contaminated soils improves the overall health status of the immediate ecosystem leading to eco-recovery and crop growth [74]. However, the efficacy of the compost applied on degraded soil to a large extent is dependent on the composition of microbial inoculum used in the composting process and the concentration of limiting nutrients available.

Like most agricultural and organic waste, *Eichhornia crassipes* could be composted in exposed space as windrows or vessels. Through the optimization of composting temperature conditions, biosafety issues would be taken care of at the hygenization stage. In order words, as compost attains maturity, sanitation evident by the destruction of both pathogens and weed propagules would have taken place during the thermophilic stage of the composting process. It is essential to note that unlike most compost from other aquatic weeds that are faced with management concern of the possibility of invading unaffected land areas like alligator weed (*Alternanthera philoxeroides*) for instance,

*Eichhornia crassipes* survives mainly only on water [75].

The phases of composting are.

**1. Mesophilic phase (25-40°C).** This phase initiates the composting process. It starts at ambient temperature which equates it the surrounding environmental temperature. Primary decomposers such as the fungi, bacteria, and actinomycetes starts to act on the material after few hours or days. These microbial actions emit heat up to about 45°C. This increase in temperature is attributed to microbial activity. Simply degradable protein and sugar-rich materials are used as carbon and nitrogen sources through microbial synthesis to generate heat. At this first composting phase, acids (mostly associated with -COOH) are produced as a result of the decomposition of soluble compounds, such as sugar causing a drop in pH of the composting material to about 4.0 or 4.5.

**2. Thermophilic phase (45-70°C).** This stage succeeds the first stage. As the compost

feedstock reaches temperatures higher than 45°C, thermophilic microorganisms gradually colonize the system [76]. These organisms, which are mostly bacteria and actinomycetes accelerates the degradation of more complex carbohydrates, fats, and proteins such as cellulose, hemicellulose, wax, and recalcitrant carbon (lignin) which serve as a carbon source for the organism. At this phase, nitrogen is being transformed into ammonia. This consequently, leads to a rise in the pH from acidic to almost neutral. Temperature also rises from 45°C to about 70°C as more energy is required for the breakdown of these complexes. Pathogen-killing and sanitization of the compost are some of the characteristics of this phase. Heat generated destroys disease-causing microbes such as *Escherichia coli* and *Salmonella spp.* Weed seeds, propagules, spores of phytopathogen fungi, helminth cysts, and eggs are being eliminated at temperatures above 55°C [77]. This could account for the reason some literature calls the stage hygienization stage [77].

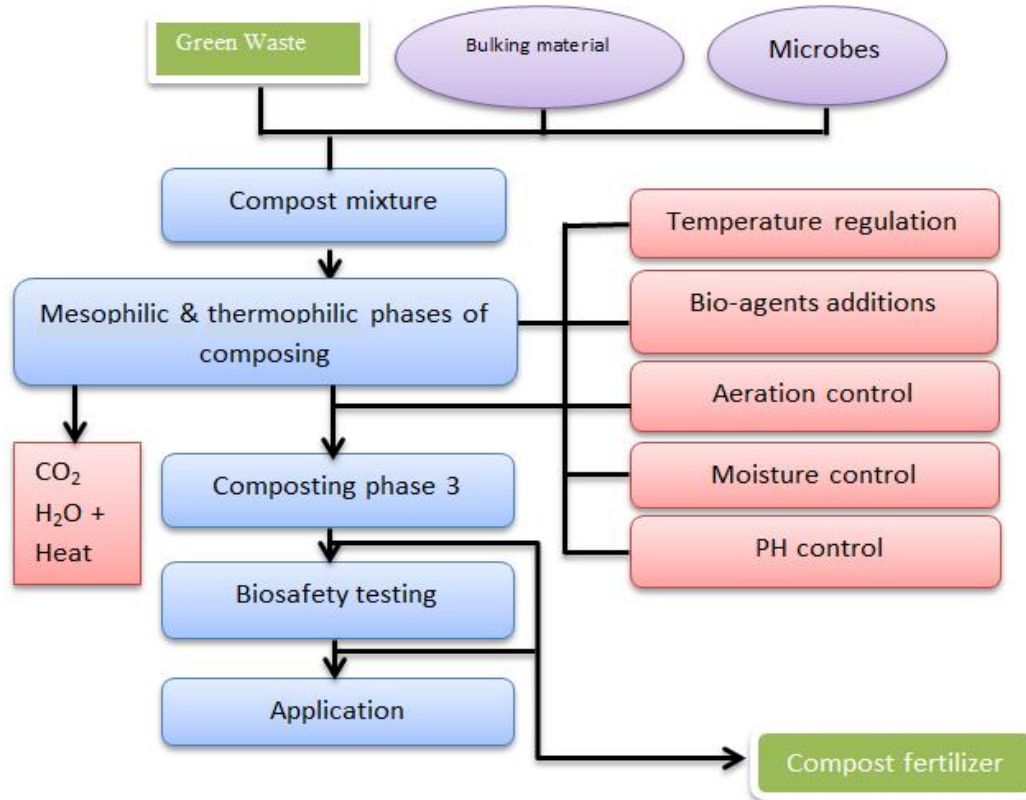


Fig. 2. Composting process flow diagram

**3. Cooling or Mesophilic phase II.** This stage follows the thermophilic stage. During this period, C and N sources (substrate) in the compost material are used up by the thermophiles, internal compost heat (temperature) begins to decrease and gradually drops to about 40–45°C. Mesophilic organisms recolonize the system and resume the activity of oligosaccharides, sugars, and protein degradation. PH slightly drops but remains slightly alkaline. Visible structures are also being produced by some fungi at this stage. The cooling phase may extend to several weeks and is sometimes mistaken for the curing phase.

**4. Maturation phase.** This stage is regarded as ‘curing’. Here, a hummus-like product is formed. Microbial metabolic activities are insignificant when equated with to other preceding phases hence its stability as there is resistance to further biodegradation by compost organic matter. This is evidenced in the respiratory index that usually falls within 0.5 and 1.5g<sup>-1</sup> OMh<sup>-1</sup> for a stable compost product. Successive steps of the entire microbial communities are also altered.

### 3.1 What Role does Microbes Play in Composting? (Microbiology)

Composting is a microbial biotechnological process. Here, diverse groups of microbes and nematodes act on biodegradable organic waste material converting it into a stable, sanitary, hummus-like product [78,79,71,72,73]. The process involves both hydrolysis and fermentation reactions [80]. The product is significantly reduced in bulk and can be employed in soil enhancement. The process of composting is initiated by mesophilic heterotrophs such as *Pseudomonas sp.*, *Streptococcus sp.*, *Listeria sp.* As the temperature rises, thermophiles replace mesophiles. The heat emitted due to the activities of microbes causes a temperature rise. This is significantly important since it sanitizes the system by killing all propagules, weed seeds, and pathogens in the compost. This activity may perhaps be an explanation of why microbes in cured mature bio compost have shown to be effectively suppressing the growth of some infectious organisms [81,82]. At the ultimate stage of the decomposition process, the mesophile recolonizes the system and becomes predominant. As the compost stabilizes, no significant microbial metabolic activity takes place. Cooling and maturation also ensue at this stage. Apart from the mesophilic bacteria and fungi, anaerobes, *Clostridium sp.*, for

example, have also been implicated at this phase [82,83].

The composting process can be considered to be a form of organotrophy as a succession of different microbial communities through the composting stages to a great extent are dependent on the organic compounds utilized for nutrition and energy [84]. The chemical composition of these organic compound and other variable conditions within the composting system also has a role to play in determining the group of organisms implicated at any composting stage [83,79] even though the three key stages in composting are commonly thought to be primarily temperature instigated [83,84]. In addition to the use of temperature fluxes as a tool for compost advancement monitoring, the presence or absence of certain species or groups of organisms can be used as indicators for maturity, stability, quality, and biosafety throughout any composting process [83,78]. Examples of this indicator organism are the *Bacillus sp.* or *Actinobacteria sp.* predominant at the mesophilic phases of composting [85] and non-endospore forming *Bacteroides*, *Chlorobacteria*, and *Planctomycetes*, whose *copiousness* is more in a matured compost when compared to the mesophilic phase [84,83]. A taxonomic shift in some microbial communities (*Actinobacteria* for example) are also been identified in mature compost [86]. We can therefore conclude that the nature of biomass used as feedstock, physicochemical parameters, and operating conditions account for bacterial, fungal, and archaeal communities present at each composting stage.

### 3.2 Factors that Affect Composting

Microbial decomposition is a key indicator of composting activity. Therefore, all parameters that influence microbial activity are likely to affect the quality of generated compost. As microorganisms with varying systems and metabolic functions are the main drivers of composting process, it, therefore, gives a clue of how complicated compost biological and chemical responses are and the extent it could be influenced by variable factors which may include but not limited to inoculum concentration, input material (feedstock), Carbon content, N, additives, bulking material, percentage moisture content, degree of aeration, levels of acidity or alkalinity, turning frequency and temperature [87,88]. Table 1 gives an overview of factors affecting composting while Table 2 summarises



the problems and solutions that could result when optimum acceptable conditions are not maintained.

### 3.2.1 Ratio of carbon to nitrogen

The proportion of Nitrogen (N) and Carbon (C) components of the material fed into a composting system is used to calculate the carbon to nitrogen ratio often referred to as the 'C/N ratio'. The C/N ratio of any material to be composted by any technology of choice is one of the key factors that could affect the rate of material biotransformation. For example, excess of C is an indication that there is more carbon-rich material than nitrogen-rich material in the composite mixture. This has been reported in the literature to have a cooling effect on the composting system thereby slowing down the microbial degradation process. To mitigate this occurrence, nitrogen-rich material should be introduced until a C/N ratio of about 25:1 is achieved. On the other hand, If the nitrogen component is overly higher than the carbon (C: N ratio < 15:1), the system will tend to experience surplus heat generation. The addition of carbon-rich material such as sawdust and dry leaves could be a solution. Therefore, to ensure that the right ideal ratio of nitrogen to carbon is maintained to drive optimized microbial decomposition, twenty-five-to-thirty-five-part carbon to one part Nitrogen should be maintained.

### 3.2.2 Moisture

Moisture is a critical factor that drives almost all biological reactions. The percentages of moisture content of the composting setup significantly affect the rate of microbial metabolic process that supports biodegradation. The biomass degradation rate is affected when moisture is either in excess or insufficient. If the percentage moisture content is extremely inadequate that is, less than 45%, the microbial activity would be retarded thereby making microbial degradation and transformation of organic materials difficult. Addition of liquid substrates, fresh fruit, and vegetable waste can aid in regulating compost moisture. Conversely, if there is an excessively high level of moisture in the compost system; degradation speed declines. Anaerobic condition ensues as oxygen is displaced. Exudation of ammonia-like odour is a clear indication of anaerobiosis. Amendment with a carbon-rich material such as the dust from sawmills or dry leafy materials could be a solution to the

problem. We can therefore say that a percentage moisture content of less than forty-five is considered insufficient while Moisture content above sixty-five is considered as excess.

### 3.2.3 Oxygen availability

The rate at which oxygen (O<sub>2</sub>) is pumped into a composting system affects the general performance of the process. As composting is an O<sub>2</sub> driven biotechnological process, it therefore critical for the microbial carbon oxidation process that results in the release of carbon dioxide, heat, and water. Oxygen can be incorporated into the system with the support of a manual agitator or an automated air-pumping machine. In the absence of oxygen, an anoxic condition ensues resulting in the death of the aerobes driving the process. Foul odour likened to ammoniac smell is a popular sign of anaerobiosis. For a rapid composting process, O<sub>2</sub> concentrations (aeration) of more than 5% are often proposed.

### 3.2.4 Temperature

Temperature (T) is one of the variable factors critical to every composting process. It is a key visible indicator for every phase of the bioprocess following the open temperature determined loop. (mesophilic → thermophilic → mesophilic. loop.) Temperatures between 25°C and 45°C initiate the composting process. This is the reason why organisms that grow in moderate temperatures (mesophiles) are the ones present at this first stage of the composting process. As heat within the compost increase from 45°C to about 75°C, thermophiles succeed in the process. At this stage, sanitization takes place as heat generated destroys all toxic substances including weed seeds and pathogens. Extremely high temperature (>75°C) can either kill or inactivate the microbes thereby impeding the on-going biodegradation process. A solution in cases of high heat is increased turning frequency and/or the addition of more carbon-rich material. Conversely, the very low temperature would elongate the period required for the compost to attain maturity and becomes stable.

### 3.2.5 PH Value

Regular taking of pH reading of the compost is important as it provides information on the compost microbes, amount of organic acid present as well as nitrogen to carbon ratio. Microbial activities are optimal between neutral and slightly basic pH ranges. A pH of less than



4.5 is indicative of excess organic acid and could be adjusted with the addition of N-rich materials until the right C: N ratio is achieved. However, pH greater than 8.5 is an indication that N is excess. This, also, could be adjusted by the addition of carbon-rich material like sawdust or leave pruning.

**3.2.6 Particle size the biomass**

Since microbes perform through organic pellets, shredding the material into smaller pieces would likely increase the areas available for microbial

actions, maintain adequate porosity for proper aeration, promote microbial activities as well as accelerate the rate of biomass breakdown. On the contrary, particulate-size should not be too small to prevent the flow of air. A reduction in composting oxygen content leads to a decline in microbial activity [89]. Therefore, the surface area of material must be put into consideration before loading it in for composting. According to Ge et al. [90], the sieving method should be adopted when considering the distribution of the particulate size of compost material.

**Table 3a. Overview of factors that affect composting**

Factor	Significance
Carbon-Nitrogen Ratio (C: N)	Carbon- nitrogen ratio ( <i>C: N ratio</i> ) helps to stabilize pH to that which would promote microbial activity. Low or high <i>C/N ratios</i> either elongate composting time, slow down the speed of material degradation, or lead to a release of pungent ammonia-like odours.
Moisture	Microbial activity thrives at moisture contents between fifty and sixty percent v/w. Both surplus and inadequate moisture limit O <sub>2</sub> availability thus affect the composting process.
Oxygen concentration	Microbial carbon oxidation results in the release of CO <sub>2</sub> . In the absence of oxygen, an anoxic condition ensues resulting in the death of the aerobes. A foul odour is a consequence of an anaerobic state. For a rapid composting process, O <sub>2</sub> concentrations (aeration) of more than 5% are suggested.
Temperature	Rise in temperature or heat that is emitted during composting results from inherent microbial activity taking place. This can be summarized as follows: From 25°C; biodegradation initiates. 40°C to 60°C active pile. 60°C to 70°C; sanitization ensues. Above 75°C, composting halts.
Composting time	Most factors ( <i>C: N ratio, O<sub>2</sub> availability, moisture, particle size, mixing, and temperature, etc</i> ) affecting composting has either a direct or indirect influence on the time to stability and maturity of compost.

**Table 3b. Composting Problems and Solutions**

Parameter/Factors	Problem	Solution
Low Aeration	Insufficient water evaporation, generating excessive moisture, and anaerobiosis environment	Turn the mixture and or add structuring (bulking) material that allows aeration.
Excessive aeration	Drop in temperature and evaporation of water, causing the decomposition process to stop due to lack of water	Shred material to reduce porosity/permeability rate and hence, aeration. Regulate moisture with fresh fruit and kitchen waste, grass, or liquid.
Insufficient Moisture (<45%)	Can halt composting due to lack of water for microorganisms	Regulate moisture with fresh fruit and kitchen waste, grass, or liquid.
Insufficient Oxygen/surplus water content	Too wet material, oxygen is displaced. Can develop zones of anaerobiosis	Constantly agitate the mixture and/or add dry carbon-rich material e.g., corn stalk, shredded waste paper.
Excess of Aeration due to particle size 30cm	Oversized materials forming aeration route, temperature drop, and process decelerate.	Chop /shred the material up to an the average size of 10-20 cm.
Compaction due to particle size <5 cm	Clog resulting from finely pulverized particles restrict airflow within the material and causing an anaerobic condition	Agitate and/or introduce larger surfaced particles to the mix

### 3.3 Biosafety

The outcomes of compost toxicity and biosafety assessment depend on the degree of temperature attained by the material during its composting process. This usually occurs during the thermophilic phase where temperature rises to 75°C and destroying or inactivating pathogenic bacteria and other harmful elements on the compost. This stage is also known as the hygienization phase. Factors such as the use of contaminated feedstock from the shovel used for bulking or mixing, or fresh material which in some case may be added after the thermophilic phase could lead to recontamination of material. Mature compost should not contain compounds which can contaminate the environment or toxic to plant [91,92,93]. Exposure pathways such as dermal contacts and ingestions are the possible routes of contamination by compost. It is essential that other variable factors that contribute to the compost attaining its desired temperature height be optimized [94]. That way, biosafety issues in compost would be adequately taken care of.

### 3.4 Other Products from Water Hyacinth

#### 3.4.1 Resource recovery using biochar

*Eichhornia crassipes* biomass has recently been employed as the renewable feedstock for biochar production used in the bio-fertilization process as both macro-and micro-nutrients or as a bioenergy source [95,96]. Biochar, an outcome of organic matter pyrolysis, impact on carbon footprint by its ability to store soil carbon or over a century (>100 years) when incorporated into the soil and can therefore contribute to the offset of carbon emissions associated with the burning of fossil fuels such as coals and flaring of gas [97]. As pyrolysis takes place at temperatures between 300-900°C, there is a relative low risk of introducing a harmful substance into the soil.

The potential of *E. crassipes* biochar in eco recovery is significant when it comes to crude oil bioremediation. This is specifically due to its great affinity to absorb both organic and inorganic pollutants, as well as its diverse functional group and large specific area organic carbon content [98,99,100]. Conversion of Water Hyacinth into biochar for application to soil, as well as the product of their co-compost is a practical example of waste (weed) transformed into a resource material for carbon capture in the soil, improvement of soil productivity, and ultimately restore lost ecosystem.

The ability of biochar to mitigate nitrogen loss [101], improve particulate airspace (porosity and permeability), organic matter degradation, as well as absorb excess moisture and heavy metals during an organic composting process [102,103,104] and its capability to lowers ammonia, improve humification in lignin-rich (water hyacinth for example) compost waste [105], reduce atmospheric emission of greenhouse gasses (GHG's) to improve the quality, curing/ maturation time of compost [106,107] has drawn its interest to scientific researchers in past decades. Additionally, the rate of nutrient percolation through soil matrixes is significantly reduced with biochar additions. This increases nutrient availability for plant and microbial use; usually in a slow-released manner resulting in greater remedial efficacy and crop yield [108]. Pyrolysis condition and the physicochemical composition of raw material used in biochar making process play a significant role in determining the nutritional value of the product [109]. It is noteworthy that biochar is not a substitute for fertilizer but acts on a complementary capacity as it significantly enhances the appraisal score of the microbiological activities taking place in the soil through, respiration indices, metabolic quotient, enzymatic activities, and biomass phytochemicals compositions that contribute to soil fertility.

**Table 4. Applications of *E. crassipes* biochar**

Biochar feedstock	Recovered substance per gram	Pyrolysis temperature	Time	Reference
Water Hyacinth + Zeolite	11.53P/g Phosphorus and 8.51HA/g Humic Acid	450°C	2h	[110]
Water Hyacinth in artificially polluted water	31.55 mg/g Fe <sup>2+</sup> 22.03 mg/g Zn <sup>2+</sup> 16.81 mg/g Cu <sup>2+</sup> 12.17 mg/gMn <sup>2+</sup>	450°C	2h	[110]

### 3.4.2 Resource recovery by anaerobic digestion (Biogas slurry)

A semi-solid waste from biogas production through anaerobic digestion (AD) process referred to as 'biogas slurry', is economically attractive due to its available N, P, and, K component for microbial use [110]. An anaerobic slurry can serve as compost amendment material used for N:P: K adjustment and to enhance the functional capacity of the indigenous microbial communities [12]. The use of biogas slurry as a compost technology product for oil spill clean-ups has not been fully explored by researchers.

Apart from the utilization of digestate in bio fertilization to stimulate microbial-mediated degradation, it can also act as a nutrient source that can support plant growth. Digestate/ slurry from anaerobic fermentation of either water hyacinth extract water and slurry are high-quality organic fertilizers that contain almost all nutrients needed to support plant growth [111] and have to promote effects on plant growth. The biogas slurry from the fermentation of water hyacinth juice contains 1.0–1.5 kg N, 0.42–0.68 kg P<sub>2</sub>O<sub>5</sub>, and 0–4.8 kg K<sub>2</sub>O [112]. To investigate the impact of *E. crassipes* digestate as a nutrient supplement for agricultural application, substituted 25% of chemical fertilizer with the digestate. There result revealed a 20-g increase in weight of single peach (*Prunus persica*) fruit, an 18.4 kg growth in production per tree, 6.3% higher fruit soluble solids, and a 14% rise in the sugar content [113].

Xi et al. [114] performed a 28 days laboratory-scale anaerobic composting experiment in a 34 L reactor. The biogas slurry from the anaerobic fermentation (composting) process was applied on crude oil polluted soil to assess its bioremediation efficacy. Results from the experiment revealed enhanced organic matter degradation, increased germination index by 18.0, and also led to a 12.8% increase in TPH biodegradation. Conclusion, therefore, is drawn that, biogas slurry is a possible microbial activator for effective application on crude oil polluted sites.

## 4. INNOVATIVE USE OF COMPOST TECHNOLOGY FOR REMEDIATION

Environmental pollutions are caused by petroleum hydrocarbon alongside other forms of ecological contaminations such as Man

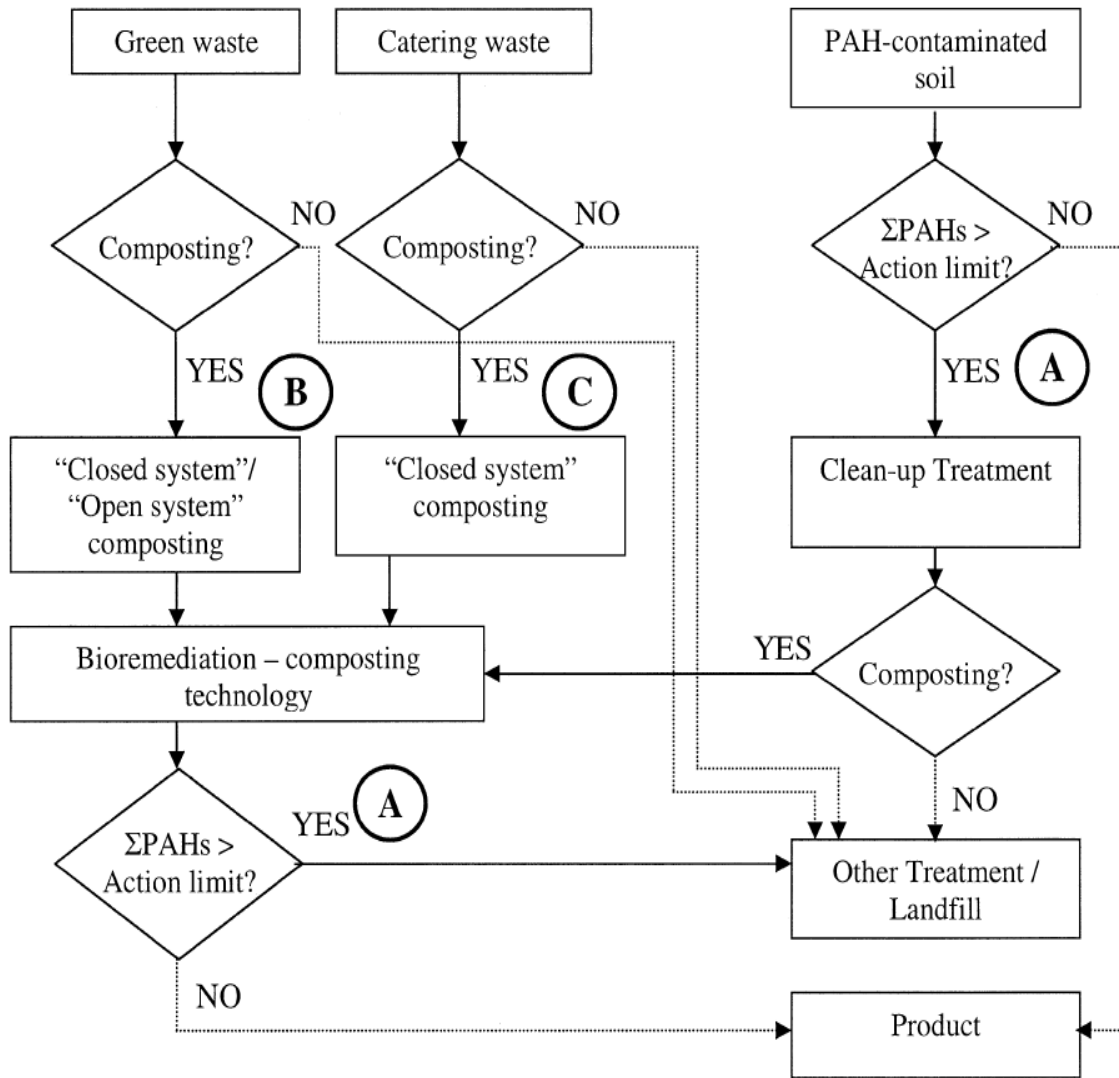
engineered industrial and agricultural waste polluting the earth. Compost bioremediation is an innovative technology that is presently being used to restore environmental matrixes. Water hyacinth through a bioconversion into organic fertilizer (compost) can also be harnessed for the management of these environmental pollutants such as crude oil and its derivatives, volatile organic compounds (VOCs), stormwater, control odours. The product of composting process used in bioremediation of polluted soil can be considered as either "tailored" or "designed" to degrade specific contaminants at a given pollution site [115]. Compost bioremediation refers to a process by which environmental contaminants on the surface and sub-surface soils are broken down into simpler, less harmful chemical component or mineralized into carbon dioxide, water, and salts by the addition of a help of a biological system in a matured cured compost [116]. Different types of contaminants, like heavy metals such as Cd and Hg and petrochemicals like the lube oil, has also been proven to either be degraded or altered by the application of compost bioremediation technology [116]. As prime target/goal of any remediation project embarked upon by any project team is to bring back the site to its pre-contamination condition. The polluted soil is either amended with nutrients or augmented with microbes to attain the desired result. Application of compost to polluted sites does not only reduce contaminant levels but also provides a soil conditioning effect, supplements inadequate nutrients and enhances plant growth [116]. Some applications of Water Hyacinth compost in pollution clean-ups are shown in Table 4 of this review.

The application of compost technology in remediation helps to stimulate microbial synthesis that results in the reduction of hydrocarbon pollutions in different soil types (clay, silt, and sandy) with a high initial total petroleum hydrocarbon concentration (TPH) of up to 380,000 mg kg<sup>-1</sup> [124,6] as well as Polyaromatic hydrocarbons PAH up to 2832 mg kg<sup>-1</sup> [125]. The Fig. 3 demonstrates what environmental regulators could consider at different stages while remediating PAH polluted sited using composting technology. A, indicates actions set for soil PAH concentration. B, specifies organic/green waste transformation into compost while C, indicates parameters considered while composting kitchen or animal waste.

**Table 5. Some applications of Water Hyacinth compost in bioremediation**

Compost Material/Feedstock	Method/Form of Application	Aim	Findings/ Result	Reference
Water hyacinth + biochar	A 20-day batch composting using a rotary drum.	To examine the probable effect of biochar addition on fibrous waste.	1. Biochar addition improved compost nutrient quality 2. Organic matter degraded with a steady speed of 0.029 in one day 3. Amendment 2.5% biochar increased Total Nitrate and Nitrite content from an initial value of 1.10% to 1.75%	[2]
WH, Cow dung, Palm Kennel Fibre, and Poultry droppings	Compost pots remediation	To monitor the degradation of TPH of crude oil contaminated soil by water hyacinth either in a single or combined application	TPH reduced significantly in both single and combined setups	[117]
Fresh Water Hyacinth and Powdered Water Hyacinth	Remediation of diesel polluted soil by bio-stimulation	To access the efficacy of fresh and powdered WH	Polluted Soil with fresh WH amendment showed a reduction in Total petroleum hydrocarbon (TPH) content.	[118]
Water Hyacinth Dry Powder	Laboratory bench-scale bioremediation of mangrove soil contaminated soil hydrocarbon	To investigate the ability of WH powder to supply limiting nutrients required for microbial oil eaters	75% loss in TPH was recorded on the 70 <sup>th</sup> day	[119]
Dry Water Hyacinth powder	<i>Ex-situ</i> treatment of heavy crude-oil polluted soil	To ascertain the bio-stimulatory effect of water Hyacinth at different crude oil concentrations	4. WH could remediate crude oil contaminated soil above 3-4.5 % equivalent to 9.70 liters/m <sup>2</sup>	[120]
Compost and inorganic nutrient	4weeks remediation of artificially contaminated engine oil set in a complete randomized design	To determine the capability of compost to influence bacteria degradation of spent engine oil was determined	87% reduction in Total petroleum hydrocarbon against 62% of inorganic fertilizer on 5% spent engine oil contamination	[121]
W H + cow dung + + Sawdust + Kenaf plant	One month five-ratio pot experimental design	To examine bioremediation of industrially polluted soil using the compost plus plant technology	1. Compost alone reduced manganese, iron, Zinc Copper and Chromium by 49±8%, 32±7% 29±11% 27±6%, and 11±5% respectively from the polluted soil. while treatments with 'compost+ plant' remediated Manganese, Iron, Zinc Copper, and Chromium by 71±8% 63±3%, 59±11%, 40±6%, and 5±4% respectively. 2. Compost addition had a significant impact on values of electrical conductivity and pH	[122]
WH, in comparison with Mexican sunflower and Bermuda grass	In-situ bioremediation using bio-stimulatory technology for an aged crude oil polluted soil	To determine the effect of compost combination on bacteria diversity	Bio stimulation favoured <i>Pseudomonas bacteria sp</i> which showed to dominant in Water Hyacinth compost	[123]

\*WH: Water hyacinth



**Fig. 3. Controlled considerations for bioremediation of PAH-polluted soil adopting composting methodologies adopted from Antizar-Ladislao et al. [125]**

**4.1 Compost Remediation Monitoring Parameters**

Several factors are key to the success of crude oil pollution clean-up using compost technology. In other words, for any ecological recovery process including crude oil polluted soils to be successful, several critical factors come into play. The presence of microbial enzymes that catalyzes crude oil degradation as well as microbial availability to the pollutant is a critical factor to consider [126,127]. Soil characteristics and properties such as consistency, water holding capacity, and organic content as well as biochemical and molecular structures can affect

the bio-availability of the microbes to the contaminants. In other words, successful remediation of crude oil contaminated soil involves an interplay between the physicochemical property of the contaminant of concern (COCs), PAHs, heavy metals, soil, and environmental factor [128,129,130,116,127]. Discussed below are some parameters to be monitored during and after the compost remediation process.

**4.1.1 Microbial abundance**

Aerobic and heterotrophic microcosms are involved in composting and compost remediation

process. For an effective degradation of any given contaminant, the organism involved, its abundance, and distribution should be relatively consistent [116,127]. Diverse microorganisms ranging from gram positive and gram-negative bacteria, green algae like the cyanobacteria, rotifers, fungi such as moulds and mushrooms, and actinomycetes like the *Thermomonospora* spp could be found in both compost and soil. Their population (microbial population of heterotrophic bacteria) are commonly determined parameters to assess their viable counts reported in CFUs/ g of soil or compost. These organisms reported by several authors have been used for bioaugmentation application on crude oil polluted soil [131,132,133,134,135]. Bacteria are the dominant group of organisms with the most biodegrading potential amongst which *Pseudomonas*, *micrococcus*, and *Rhodococcus* are the key players [136,135,131]. *Bacillus* sp. isolated from compost such as animal manures and oil sludge have been reported to degrade poly-aromatic hydrocarbon by Ubani et al. [134] it is then concluded that indigenous microbes with oil-eating abilities can be used as a bioremediation agent to restore crude oil polluted sites.

#### 4.1.2 pH value

The pH value of crude oil polluted soil can fluctuate within the ranges of 1.3 to 9.2, subject to the characteristic properties of both the pollutants and the soil [137,138]. Bacterial growth, however, is usually supported under optimal pH ranges between 6 and 8 (US EPA 2014). As microbiological degradations ensue, organic carbon materials are broken down releasing, organic acids that lower the pH value of the soil [87]. pH increases steadily with an increase in temperature due to ammonia production, which when in solution, ammonium is formed [139], Works of literature have shown that pH is a vital factor that influences microbial activity that results in hydrocarbon breakdown [140,141]. The study of Sasaki et al. [140] revealed that degradation halts at a pH value of 2, but composting may attain degradation efficiency up to 83% at pH 7. More so, the study by Yan et al. [23] on the effect of changes in pH on hydrocarbon degradation rates revealed that the lowest degradation was at pH 3 (4%) and the degradation rate was optimal at pH 7 (72%). As the pH value rise to 9, Nitrogen was no longer available to microbes as nutrient due to the formation of ammonia gas confirmed by the urine-like smell that oozes out into the

environment [142]. It is important to take pH reading to monitor the changes in pH during and after composting operation as many sites contaminated by crude oil or its derivatives do not have standardized values of pH for remediation process [143], US EPA, 2014, [127], that is conventional.

#### 4.1.3 Moisture content

The growth of microorganisms is significantly affected when the moisture content is inadequate. When soil moisture is in excess, aeration becomes poor hence, reducing airflow vital for oxygen-requiring microbial metabolic processes [144,116]. Percentage of the moisture content that would support a compost operation should range within 45 to 65 [145,116,127]. Moisture content must, therefore, be monitored cautiously throughout every compost operation to make required amendments when necessary. Also, depending on the method of compost bioremediation being considered (*in-situ* or *ex-situ*), appropriate precautions should be taken to avoid detrimental water accumulation in soils (US EPA, 2012).

#### 4.1.4 Temperature

Composting is a natural process that generates heat that causes rises in temperature resulting from microbial metabolic activities dynamically taking place through the process [146,147]. Soil temperature is a critical factor that could affect the growth, activity, and succession of microorganisms in soil and compost. Microbial activities and physicochemical properties and structure of crude oil are affected by temperature [148] and consequently, this influences the direction of composting. When the temperature rises, hydrocarbons become more volatile. This volatility enhances the bioavailability of the compound to microbes [149,150]. Seasonal variations affect soil temperatures. Bioremediation process in a season of the year when temperatures are low (the rainy period for example) is likely to be slower than sunny times of the year. Specialized organisms such as psychrophilic bacteria could be considered in cold regions for composting to cushion this effect [116].

#### 4.1.5 Soil texture

The texture of Soil determines how porosity or permeability it could be. Clay soil for example has fine particles which makes it less permeable

if compared to sandy soils which are coarser and have larger particles. During remediation, the fate of hydrocarbon could be affected by soil texture which determines vertical and horizontal distributions of air, nutrients, and water through the soil. Degradation time and efficiency are affected by the nature of the contaminant, the soil texture (the parentage clay, sand, or loam), organic matter, etc. The use of bulking agents could be a solution to the challenge of compacted soil during a bioremediation process [116]. On the other hand, compact soil may need tilling or pre-treatment such as grass mulching or core aeration before the composting process [116].

#### 4.1.6 Nature of Contaminants and concentration

During any bioremediation treatment, the fastness or slowness of microbial degradation of any pollutant can be linked to the characteristic of the contaminant of concern. The biodegradability of a contaminant is molecular weight-dependent. Lighter fractions of crude or example degrade faster than heavier weight hydrocarbon like the asphaltenes [151,152]. Likewise, Crude oil mineralization is affected by its concentration [153]. There are specific pollutants (volatiles and non-volatiles) that could kill any life no matter how minute its concentration could be while some other pollutants even at very high concentrations/dose would at most just inhibit microbial growth. It is also worthy to note that similar groups of microbes can react in varying ways to the same pollutant [154,11]. When highly volatile fractions such as the BTEX chemicals are predominant with a contaminated site, or if a high amount of recalcitrant organic pollutants is involved, the nature of these forms of contaminant will negatively impact the microorganisms likewise the overall remediation process. Therefore, the biodegradation rate of crude oil polluted soil depends on concentration, chemical composition, and nature of the contaminant of concern [155,156]. In an increasing biodegradability order, the following hydrocarbons can be arranged, thus; asphaltenes < poly aromatics < cyclic alkanes < mono aromatics < low- molecular weight alkyl aromatics < branches alkanes < linear alkanes [11]. Where petroleum hydrocarbon concentrations are extremely high, microbial activities total is being disrupted due to the toxic effect hence, limiting biodegradation potential [157]. On the other hand, where the total

petroleum hydrocarbon concentrations are extremely low, biodegradation can be limiting as well. This is because carbon source for microbial support growth is limited [153]. Typically, as the molecular weight of pollutants decreases and the chemical structure complexity of hydrocarbon becomes simpler, degradation rate increases [158]. As baseline assessment (physicochemical and structural assessment) of both crude oil and the contaminated soil are essential for successful bioremediation process [158], Scientific report now concludes that bioremediation process can be affected by (1) pollution type (2), pollutant concentration, (3), Pollutant-Microbe interaction (4) pollution environment, (5) nature of pollutant [159,116].

#### 4.1.7 Availability of nutrients

Availability of nutrients either from compost or other organic or inorganic sources play important role in microbial activities [160,158]. Microorganisms can be stimulated to enhance their oil-eating potential. This can be done through the supply of adequate available inorganic nutrients elements such as N and P that are vital for development support and to their activity in crude oil biodegrading [161,162,126,127]. N and P are considered as the '*limiting nutrients*' based on Liebig's Law of the Minimum. In most cases, nutrients are available in insufficient amounts in hydrocarbon polluted land terrestrials and hence, the need for nutrient supplements [156]. In a review done by Varjani et al. [11], he stated that as petroleum hydrocarbons do not contain sufficient nutrients such as nitrogenous and phosphate element (N and P) essential for microbial growth and metabolism, C: N: P: K ratios could, however, be amended with organic fertilizers like compost or inorganic fertilizers such as the N-P-K chemical fertilizers. As the carbon in the petroleum serves as the carbon source for microbes, nutrient (N, P) ratios as reported by researcher as 10-part nitrogen to one part phosphorus is required to promote microbial growth and to stimulate hydrocarbon degradation [144,163,164,165,161,162,145,127]. Both seeding of polluted site or laboratory scale remediation setups with crude oil-degrading microbes and bio-stimulation with nitrogen-rich biofertilizers shows an accelerated crude oil breakdown by oil-eating microbes. However, when there is an excessive amount of nitrogen in the soil, microbial growth could be inhibited. When the concentration of Nitrogen-phosphorus-potassium is in excess, the biodegradation



activity of hydrocarbon pollutants is equally halted [160,166,11].

#### 4.2 Limitations of Remediation by Composting Technology And Way Forward

The methodologies applied in today's soil compost remediation are constrained by the following factors.

- (i) *Product size*: As compost fertilizer is a volumetric product, its application as soil amendment material often increases landfills. Composting process requires space whether in-situ or ex-situ and this could pose challenges in areas or communities with limited space.
- (ii) Also, there may be occurrences of an uncontrollable release of volatile organic compounds (VOCs), especially where polluted soil is to be evacuated for ex-situ treatment with compost. These compost emissions that are capable of negatively affecting air quality are often neglected and yet to be given the urgent attention it deserves. is suggested for future biodegradation studies,
- (iii) *Quality of Water Hyacinth Based compost*: The ability to absorb heavy metals and other toxic organics can pose a challenge to its quality composts. These heavy metals could be carcinogenic chemicals of concern (COC's) to the recipient through dermal or ingestion pathway hence, a gateway to increased human health and environment.
- (iv) *Enzymatic/ genomic composition*: little is known about hyacinth composting and Whole-genome sequence and gene coding specific enzymatic function in contaminated soils remediated by Water Hyacinth composting or compost application. Hence, next-generation sequencing and bioinformatics pipeline are suggested to be deployed to identify key enzymes and genes indigenous water hyacinth hydrocarbon- bacteria, lignocellulosic bacterial particularly in the thermophilic stage. From this suggested future study more knowledge will be established on the biodegradation mechanisms (either a metabolic process or where the process is considered synergistic) of the composting technological systems
- (v) *Asphaltene Bioavailability*: Knowledge is limited on the bioavailability of recalcitrant heavy crude oil contaminated soil to the water hyacinth product in case of long-term bioremediation of aged pollution.
- (vi) *Compost parameter Optimization*. A composting process can be optimized by considering the application of design experimental models using operational parameters, such as frequency of aeration, percentage moisture content, and C/N ratio as variable factors. Depending on the soil property, and nature of the contaminant, and the scale of the setup that is whether it is a bench-scale, pilot scale, or field trial, compost operation conditions could be affected. Therefore, it is suggested that future research should delve into the area of optimization to help shorten compost process time, with increasing efficiency making the product replicability and scalability of the product by various researches

#### 5. CONCLUSION

Water Hyacinth based compost and biochar are a product that applies the principle of green chemistry due to its environmental friendliness and also for being products of simple, cost-effective scalable and practicable technology application for successful remediations of crude oil contaminated soil especially in South-South, Nigeria where both crude oil pollution and Water Hyacinth are ravaging ecosystems. The science, technology, and microbiology of these bioconversion processes must be well understood alongside parameters affecting composting and bioremediation processes such as temperature reading, percentage moisture content, pH, O<sub>2</sub> levels, and C/N proportion microbial abundance, contaminant concentration that need to be monitored and controlled. Public awareness of these processes, however, is the way forward to positively impact livelihood, food security and essentially restore the lost ecosystems.

#### ACKNOWLEDGEMENT

We are thankful to the World Bank African Centre of Excellence in Oilfield Chemicals Research (ACE-CEFOR).

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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