East African Journal of Environment and Natural Resources
eajenr.eanso.org
Volume 7, Issue 2, 2024
Print ISSN: 2707-4234 | Online ISSN: 2707-4242
Title DOI: https://doi.org/10.37284/2707-4242

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda

Waliyyah Nabukeera Kibira[1], Prof. Ademola Aremu, PhD[2] & Dr. Sowedi Masaba, PhD[3]*

[1] Pan African University Life and Earth Sciences Institute, (including Health and Agriculture) Ibadan, Nigeria.
[2] University of Ibadan, P.M.B 20, Ibadan, Nigeria.
[3] Busitema University, P. O. Box 236, Tororo, Uganda.
[*] Correspondence ORCID: https://orcid.org/0009-0002-1713-0787; Email: kwaliyyah@gmail.com

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Date Published:

09 October 2024

Keywords:

Decay Rate, Physicochemical Parameters, Anthropogenic Impact, Hydrology, Uganda.

ABSTRACT

The assessment of ecological functions of wetland areas offers a more dependable measure of the health of these ecosystems. The study examined the decomposition process within two urban wetlands with different degree of disturbance as a means of evaluating their ecological health and functionality. The study also inspected the influence of various physicochemical parameters on rates of decomposition. 20g of Pennisetum purpureum, an increasingly common invasive species in natural ecosystems due to human activities, was harvested, air dried to a constant weight and utilised in litter bag decomposition experiments within the two wetlands. Invasive species such as Pennisetum purpureum often have similar impacts across different ecosystems, making them useful models for generalizing results. Changes in leaf mass over time and leaf breakdown rates using a single exponential decay model were determined. Wetland physicochemical characteristics (pH, temperature, TDS, dissolved oxygen & conductivity) were also measured and recorded for the two wetlands within the duration of the experiment. Pearson's correlation test was conducted to validate the relationship between the physico-chemical parameters and decomposition rates of the two different wetlands. Results revealed a significant difference in mean decomposition rates, ($p < 0.001$) with the degraded wetland exhibiting a higher value (0.20 kd-1) compared to the semi-intact wetland (0.015 kd-1). The rates of decomposition were also found to positively correlate with temperature ($r = 0.54$), conductivity and pH, while showing a slight negative correlation with TDS and dissolved oxygen. The study concluded that rapid decomposition in degraded wetlands is primarily due to human disturbances that alter their physical characteristics indicating deteriorating ecological health inform of eutrophication, altered native plant growth, subsidence, decreased carbon storage, oxygen depletion and so forth. Additionally, the alternating periods of inundation within the wetlands, caused by the wet-dry cycles is a primary influencer of decomposition rates in wetlands especially within the tropical region.

APA CITATION

Kibira, W. N., Aremu, A., & Masaba, S. (2024). Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda. *East African Journal of Environment and Natural Resources*, *7*(2), 17-34. https://doi.org/10.37284/eajenr.7.2.2285.

CHICAGO CITATION

Kibira, Waliyyah Nabukeera, Ademola Aremu and Sowedi Masaba. 2024. "Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda". *East African Journal of Environment and Natural Resources* 7 (2), 17-34. https://doi.org/10.37284/eajenr.7.2.2285.

HARVARD CITATION

Kibira, W. N., Aremu, A., & Masaba, S. (2024) "Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda", *East African Journal of Environment and Natural Resources*, 7 (2), pp. 17-34. doi: 10.37284/eajenr.7.2.2285.

IEEE CITATION

W. N., Kibira, A., Aremu & S., Masaba, "Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda", *EAJENR*, vol. 7, no. 2, pp. 17-34, Oct. 2024. doi: 10.37284/eajenr.7.2.2285

MLA CITATION

Kibira, Waliyyah Nabukeera, Ademola Aremu & Sowedi Masaba. "Assessing Wetland Health Through Decomposition in Degraded and Semi-Intact Wetlands in Uganda". *East African Journal of Environment and Natural Resources*, Vol. 7, no. 2, Oct 2024, pp. 17-34, doi:10.37284/eajenr.7.2.2285.

INTRODUCTION

The overarching notion of ecosystem health has been defined as the state, condition, or performance of an ecosystem with some desirable objective. Ecosystem health describes how an ecosystem can provide services to humans while maintaining its health and ability to replenish and self-generate environmental outputs (Perrings et al. 2010; Lu et al. 2015; O'Brien et al. 2016). Ecosystem health is strongly linked to stress ecology, which defines a healthy system by its organization, resilience, vigour, and the absence of signs of distress. A healthy ecosystem is considered stable and sustainable, capable of maintaining its structure, autonomy, and ability to recover from stress over time (Rapport et al. 1998). Decomposition is a crucial process for ecosystem functioning, releasing nutrients necessary for new life. Assessing litter decomposition can indicate wetland health and integrity (Tenkiano and Chauvet, 2018).

Wetland ecosystems are considered degraded following the effects from various anthropogenic (human) or natural activities, leading to a decline in its ecological health, functionality, and services (Bai et al. 2013; Crecious and Lazarus 2013; Das and Basa 2020). This degradation can manifest in multiple ways, including loss of biodiversity, altered hydrology, pollution, and reduced ability to provide essential ecosystem services, Ayanlade and Proske (2015), Nayak and Bhustan (2022) such as in Uganda, wetlands are being degraded and lost, mainly due to agricultural expansion by drainage and conversion (Gideon and Barasa 2018; Nuwagira et al., 2023). As urban areas expand, wetlands are progressively destroyed, interrupting vital ecosystem services (Kometa, 2018).

Semi-intact wetland ecosystems are those able to retain some of their natural characteristics and functions, Mitsch and Gosselink, (2015) even after being partially altered or impacted by human activities or natural processes (Dodds and Whiles, 2010; Ramsar Convention Secretariat, 2013; Meli et al. 2014). Unlike fully degraded wetlands, semi-intact wetlands still provide important ecological services and support biodiversity, though they may not function at their full capacity.

The intricate breakdown of organic substances that occurs throughout the decomposition process is a critical component of an ecosystem (Tenkiano & Chauvet, 2018) as nutrients from the environment

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

would be locked up within deceased organisms, and no new life could be formed. This process takes place in a number of sequences and can be extremely complex (Arroita et al., 2012). Decomposition occurs through three processes including leaching comminution and catabolism. Litter decomposition processes can be used to assess the health and integrity of wetland ecosystems (De et al., 2018). Understanding how wetlands respond to rapid environmental changes is critical for conservation and management (Song et al., 2021).

Litter decomposition may not be typically regarded as a wetland function, but it greatly influences various wetland functions and services, thus playing a crucial role in wetland development. Litter decomposition has a significant impact on the physical and chemical properties of wetland soils, which in turn can determine site conditions (Gingerich et al., 2014). Moreover, litter decomposition is associated with wetland functions such as nutrient availability and cycling, energy flow, primary productivity, and carbon sequestration. This is because it facilitates the breakdown and release of nutrients from plant litter (Gingerich & Anderson, 2011).

Measuring ecological processes such as leaf litter decomposition, is a direct way to assess the health and functioning of an ecosystem. This assessment can help policymakers make informed decisions based on the degree to which a system has been altered from a carefully selected reference condition. (Fuell et al. 2013). Decomposition of leaf litter is a helpful indicator of wetland functions and could be used to evaluate the replacement of wetlands in compensatory mitigation initiatives.

The decomposition rate of organic matter in wetlands is dependent on biotic, chemical, and physical factors (Gingerich et al. 2014; Mackintosh et al. 2015; Suseela 2019; Song et al. 2021). Physical variables can have an indirect effect on the decomposition rate by influencing the activity levels of the biotic communities that are present. Temperature and pH are considered to be the most accurate predictors of the rate of decomposition in the environment (Kirwan et al. 2014; Martínez et al. 2014; Petraglia et al. 2019; Xie et al. 2019). Various other studies by Sampaio et al. (2008), Cook (2014), Entrekin et al. (2015), Harbourd et al. (2015), and Yarwood (2018) have utilised these indicators to assess freshwater ecosystems.

While intact wetland ecosystems involve processes like nutrient translocation, litter decomposition, and production (Schuyt, 2005; Adeeyo et al., 2022), many of these processes are inadequately monitored. There is limited knowledge about the occurrence of litter decomposition yet understanding wetland processes and their vulnerability to anthropogenic stressors is fundamental for predicting future impacts. Wetland decomposition is a potential indicator of ecological condition and stability Tiegs et al. (2013). However, few studies, particularly in the tropics (Jabbar et al. 2000; Mitchell 2013; Kakuru 2013; Charles 2019; Kayima et al. 2018; Hedman 2019; Mandishona and Knight, 2022) have evaluated these processes including carbon sequestration potentials & hydrology alterations. However, these studies have mainly focused on direct human interactions with wetland ecosystems without taking into account the physicochemical characteristics of wetlands, impact of wet-dry cycle on wetland processes and the degree of disturbance at which a particular wetland stands.

In East Africa, particularly Uganda, most research has focused on primary production/provisioning ecosystem services (Egoh et al. 2012; Turyahabwe et al. 2013; Nsubuga et al. 2014; Langan et al. 2019; Osewe et al. 2023), rather than the regulating ecological processes. Assessments of ecosystem health typically overlook the functioning of the system as a whole, instead of favouring the study of its structural elements.

This work therefore builds on earlier studies of decomposition processes in wetlands providing an assessment of rates of decay between two wetlands

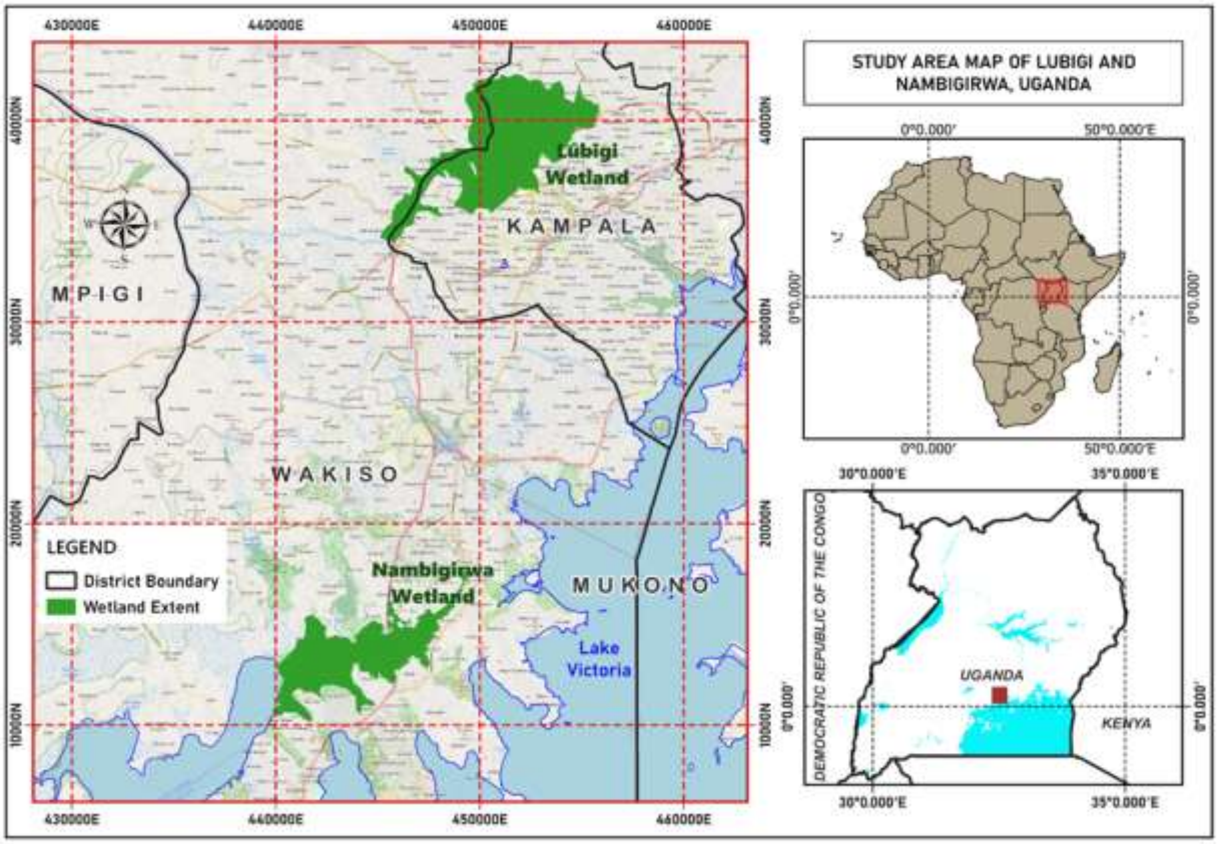
Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

of different degrees of disturbance in tropical region. The study examines the rate of decomposition between a degraded and a semi-intact wetland and analyses the effect of physicochemical parameters on decomposition. The hypothesis is that decomposition rates and their relationship with physicochemical parameters do not significantly differ between heavily degraded and semi-intact wetlands.

MATERIALS AND METHODS

Study Area Description

Figure 1: Uganda and its location in Africa, including the location of the study areas Lubigi wetland and Nambigirwa wetland



This study was conducted in two wetlands; Nambigirwa and Lubigi (Figure 1). Nambigirwa is a relatively intact wetland located in Wakiso District, measuring about 23.3km^2 and lies at an altitude of 1,143m.

Nambigirwa is a shoreline wetland found on the eastern side of Waiya Bay, extending approximately 6km inland with Kalandazi, Malumenya and Mugomba riverine wetlands acting as its tributaries. The most dominant wetland vegetation inland is *Miscanthus sp* while toward the lake is *Cyperus papyrus.* Nambigirwa wetland acts as a sediment and nutrient trap, buffering Lake Victoria and this is quite important as green spaces that would allow infiltration of stormwater in the immediate surroundings are taken up (GoU 2016). Nambigirwa wetland is facing a lot of pressure from land use activities such as settlements that have intensified and grown right down to the edges of the wetland. The Entebbe expressway that traverses through Sekiwunga and Ssisa Sub-Counties is likely to attract more settlements which will increase pressure towards the wetland (GoU 2016).

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Lubigi situated at (00^0 20’48’ N, 32^0 32’28’E), is the largest wetland having a total surface area of 0.0109 km^2 serving Kampala City, and neighboring districts to the north and western parts of the country. The wetland is part of the Mayanja-Katonga system in which water flows northward to Lake Kyoga (Gideon and Barasa 2018). Unfortunately, the Lubigi wetland has suffered illegal encroachment in the form of settlements, agriculture especially crop cultivation, dumping of waste, and draining that has severely compromised the wetland. Despite this, the wetland remains critical as a water catchment area for the central region and a significant source of water for the water-stressed areas of the cattle corridor in Central Uganda (GoU 2016).

Experimental Design

Litter decomposition was measured using the litter bag method (Aerts, 1997). In June of 2023, plant materials of *Pennisetum purpureum* were harvested from Lubigi wetland due to Nambigirwa being permanently inundated, limiting access to the plant materials and air dried for a minimum of one week (Gingerich et al. 2014). *Pennisetum purpurem* was specifically as it is increasingly common in natural ecosystems due to human activities as an invasive grass, it often disrupts natural ecosystems by altering nutrient cycles, water flow, or species interactions.

Invasive species typically grow and spread more rapidly than native species. This rapid growth makes them easier to study in short-term experiment such as this one because their effects on the ecosystem can be observed more quickly. Invasive grasses such as *Pennisetum purpurem* often outcompete native plants for resources such as light, nutrients, and space. They are commonly used to study how such species alter the wetland environment, particularly in terms of nutrient cycling, hydrology, and biodiversity loss. Therefore, utilising *Pennisetum purpurem* in this study helped to explore the mechanisms behind these disruptions and how they may lead to changes in biodiversity, productivity, and declining ecosystem health. Studying *Pennisetum purpureum* decomposition rates also provides insights into how ecosystems recover from disturbances and whether the species facilitates or hinders ecosystem restoration.

2 mm vinyl-coated fiberglass window mesh were used to make 20 X 20 cm litter bags (Benfield et al. 2017). The litter bags had three heat-sealed sides with one folded side and were strengthened with stainless steel staples spaced 5 cm apart. The amount of litter in each bag was 20 g (Aerts, 1997; Gingerich, 2010; Benfield et al. 2017). Extra litter that had gone through the same process was used to refill the bags up to 20 g (±0.1 g) before sealing at site to account for losses while handling and transporting.

To simulate natural litter decomposition, litter bags were placed either on top of existing litter or on bare ground and in the case of standing water, litter bags were submerged first so as to make the surface wet and also to minimise any hydrophobic effect that the mesh might have caused. The litter bags were tied to the stems of overgrown wetland vegetation with 1-meter-long nylon strings, and the location of each bag (3 metres apart) was marked with red waterproof tape to make it easier to retrieve later. For each site, the bags were placed both within the waterlogged areas and drier areas of the wetlands. Additionally, the human disturbance factor was taken into consideration whereby in the drier areas, the bags were placed close to grazing areas, crop gardens and walking paths.

The leaf litter bags were left at each site for three months, from late July to Early September 2023, with half of the period being dry and the other half receiving heavy rains in August. While longer-term studies are often ideal for understanding the full spectrum of decomposition dynamics, the 3-month study was still highly relevant for addressing the study’s specific objectives related to nutrient cycling and ecosystem impacts.

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Pennisetum purpureum, experiences rapid decomposition in the first few weeks to months therefore a 3-month experiment is able to capture this rapid nutrient release, offering insights into how quickly *Pennisetum purpureum* contributes to decomposition, especially in wetland ecosystems where it is invasive. A 3-month experiment on the decomposition of *Pennisetum purpureum* is highly relevant for understanding the early stages of decomposition and in ecosystems where this species is present. The experiment was also able to capture the dry and wet cycle although in the shortest time possible given it was set up at the off set of dry season, and on set of rainy season. On the day of retrieval, the bags were removed, placed in individual polythene bags, and returned for further analysis at the laboratory. Six replicates were then retrieved from each site on days 7, 14, 28, 35, 42 and 63. After retrieval, the litter from each litter bag was washed to remove mud and other non-organic debris, set on paper to dry (Benfield et al., 2017) and then the leaf litter samples were oven-dried at 65 ^{0}C to attain a constant weight.

Calculations of the Decomposition Process of Wetland Litter

Changes in leaf mass over time were measured and recorded as percent dry remaining mass. The initial remaining weight (Rw) for leaf litter at each retrieval point was determined, using the equation below:

$$Rw(\%) = \left(\frac{Mt}{Mo}\right) x100 \quad (1)$$

Where: *Rw* (%) is the percentage of leaf litter weight remaining, M_t is the weight of leaf litter (g) at the time of retrieval M_0 is the initial weight of leaf litter (g).

Litter decomposition results in a relatively stable substance build up, nevertheless, litter decomposes more quickly in the beginning and slowly over time hence mass loss is frequently explained by a single exponential model. Leaf litter decomposition rate (k) was calculated using equation 2 below

$$k = \frac{-In\,(Mt/M0)}{t} \qquad (2)$$

where Mo represents the initial mass of a sample, Mt represents the final mass of a sample respectively, and t is time (number of exposure days). According to (Harmon et al., 2009); (Equation 2) has been proven effective in determining litter decomposition rates based on short-term experiments and has been widely used for this purpose.

Measurement of Water Physicochemical Characteristics

Physicochemical parameters were measured upon deployment of the litter bags at both sites and at every after 7 days for the entire duration of the experiment. Water analyses for conductivity, TDS, pH, and temperature were done in situ using proper probes i.e. (eXact Micro pH+ multimeter for pH, EC and TDS) according to manufacturer's instructions and dissolved oxygen was fixed on site and measured at the National Water and Sewerage Corporation (NWSC) laboratory using the Winkler's Titrimetric method. Results from the multiple samples taken on retrieval days were aggregated and one mean value was obtained for all the physio-chemical parameter measurements.

Statistical Analysis

The data obtained was entered and organized in MS. EXCEL and then exported to SPSS 22 for further inferential analyses. In SPSS, the data was first tested for the assumptions of normal distribution.

To compare the mean rate of decomposition among the different wetlands (degraded and semi-intact) an independent-sample t-test was conducted. The results were presented as graphs accompanied by *p*-values. The rate of decomposition throughout the experiment was plotted against the sampling times (days).

The relationship between the rate of decomposition and the different environmental (physicochemical) parameters in the different wetlands was evaluated

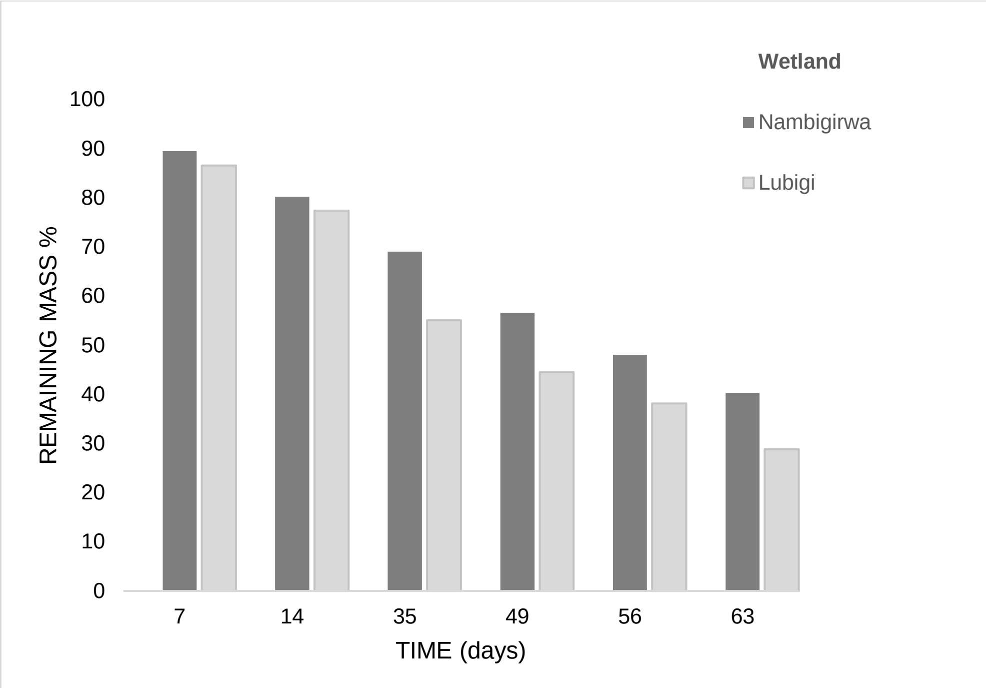
Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

using Pearson's correlation test. The relationships were summarized in a table using correlation coefficients and illustrated using scatterplots. All statistical inferences and conclusions were made at a 5% significance level.

RESULTS

Decomposition Rates

Figure 2*: Mean mass loss by percentage over time for Lubigi and Nambigirwa*



The mass remaining decreased faster for Lubigi wetland (degraded) rates faster than for Nambigirwa wetland. At 7 days, the percent mass remaining was at 85% for Lubigi wetland and 88% for Nambigirwa wetland. At 14 days, the mass remaining was 74% for Lubigi wetland and 73% for Nambigirwa wetland. At 49 days, the remaining mass was less than under 50% for Lubigi wetland. The mass remaining was by a difference of 15% between the wetlands by end of duration for the experiment (*Figure 2*).

An independent-sample t-test was also performed to compare the mean rates of decomposition for Lubigi (degraded) and Nambigirwa (semi-intact) wetlands. The results show that there was a significant difference in the rates of decomposition between the degraded and semi-intact wetlands (df = 1, 70, F= 5.89, $p < 0.001$) Table 1.

Table 1: Descriptive statistics of Rates of Decomposition between Wetland Types

	Wetland	N	Mean	Std. Deviation	Std. Error Mean
Rate of Decomposition	Nambigirwa	36	.014574	.0051887	.0008648
	Lubigi	36	.020086	.0069827	.0011638

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Figure 3: Decomposition rate between the Lubigi and Nambigirwa wetland study sites

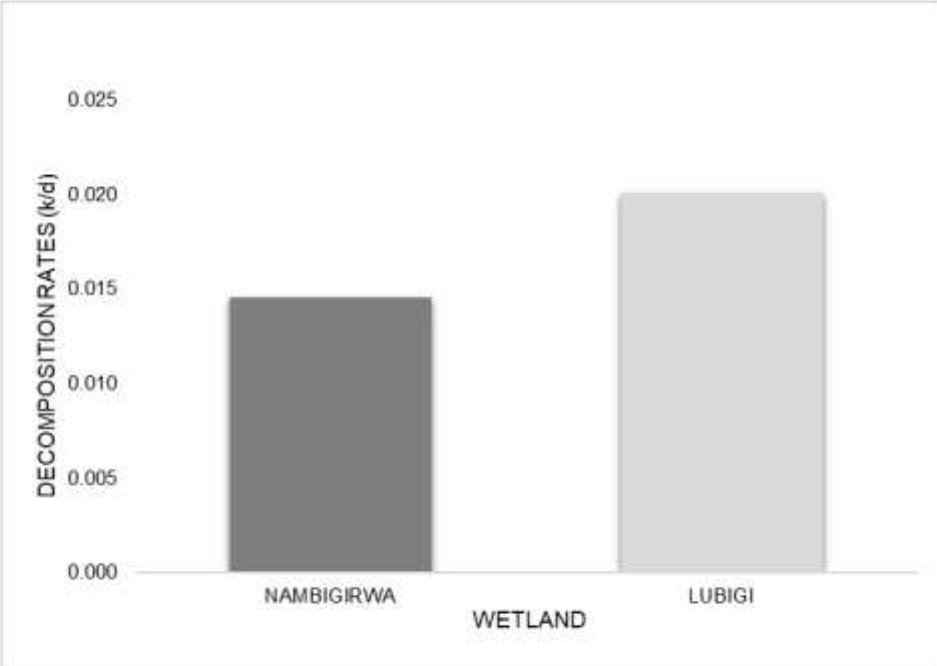


Figure 3 shows that the degraded wetland had a higher rate of decomposition (0.20±0.007 kd-1) than the semi-intact wetland which recorded an average rate of 0.015±0.005 kd-1.

Water Physicochemical Parameters

Table 3: Summary of the mean values of the physio-chemical parameters at Lubigi and Nambigirwa wetlands between June and August, 2023

Water Parameters	Wetland Areas	
	Lubigi	**Nambigirwa**
pH	6.76 – 7.12	6.17 – 6.72
Dissolved Oxygen (mg/L)	2.8 – 5.8	4.1 – 4.5
Temperature ^{0}C	22.5	23.3
Conductivity ((µS/cm)	530.5 - 596	105 - 343
TDS	375 – 432	76.8 - 638

The study findings reveal that Nambigirwa wetland had lower pH and conductivity values compared to Lubigi wetland. Nambigirwa wetland also had the lowest TDS value. Lubigi wetland had the lowest dissolved oxygen value and lower temperatures compared to Nambigirwa (Table 3).

Table 4*: Mean decomposition rates and physio-chemical parameters from the different wetland sites*

Wetland	Decomposition Rate (kd^{-1})	Physio-chemical Parameters				
		Cond	**Do**	**Temp**	**PH**	**TDS**
Degraded (Lubigi)	0.02±0.005	580±12.66	4.23±0.55	22.53±0.21	6.98±0.07	414.83±8.21
Semi-intact	0.015±0.006	216.0±43.8	4.42±0.08	23.25±0.36	6.50±0.09	219.7±89.3

East African Journal of Environment and Natural Resources, Volume 7, Issue 2, 2024
Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

(Nambigirwa)

Cond. = Electrical conductivity, DO = Dissolved oxygen, Temp = Temperature (water)

Table 4 displays mean decomposition rates and physio-chemical parameters for various wetland conditions. Lubigi wetland had the highest mean values for most of the parameters, such as conductivity, pH, and TDS. In contrast, Nambigirwa wetland had the highest levels of dissolved oxygen and temperature.

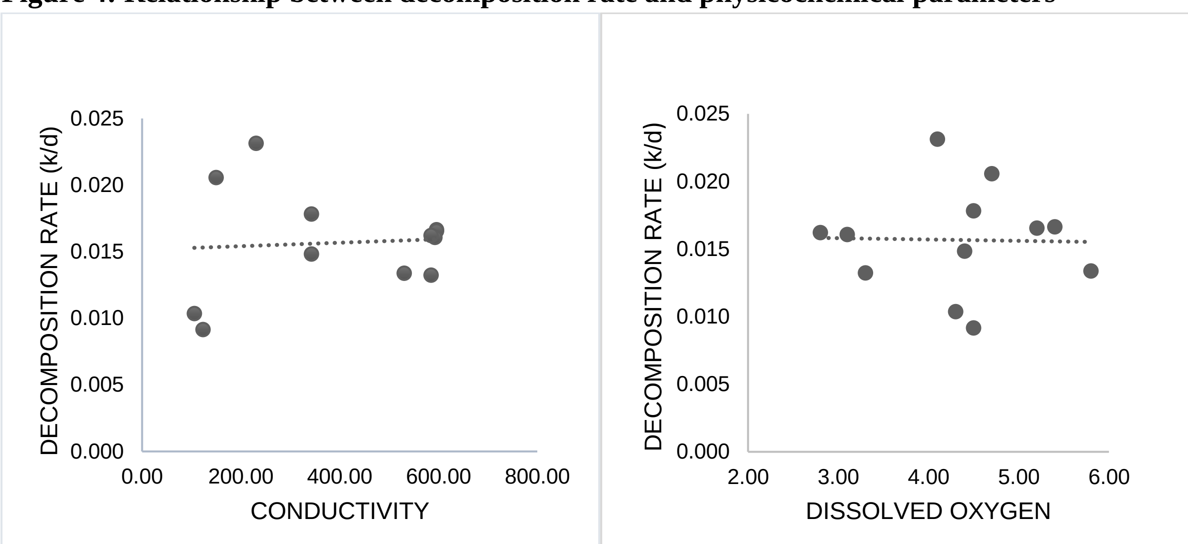
Relationship between rate of decomposition and wetland physicochemical parameters

Pearson's correlation test and simple linear regression were conducted to validate the relationship between the different physicochemical parameters and decomposition rate (k/d). The rate of decomposition (k/d) increased with conductivity (r = 0.068), Temperature (r = 0.54) and pH (r = 0.001), and decreased with an increase in TDS (r = -0.257) and Dissolved oxygen (r = -0.023). Temperature has a moderately strong positive correlation with the rate of decomposition compared to conductivity and pH as predicted as observed in the table below.

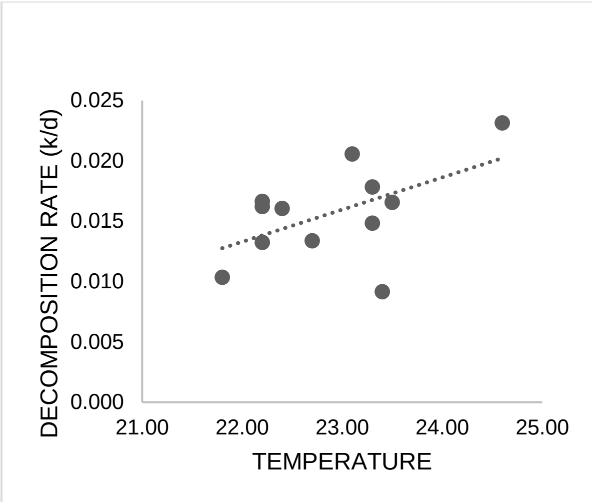
Table 5*:* Pearson correlations between decomposition and physicochemical parameters

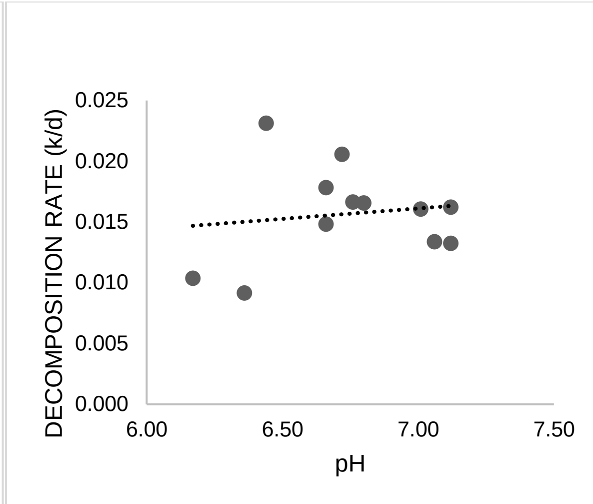
		Cond.	DO	Temperature	pH	TDS
Decomposition rate (k)	Pearson Correlation	.068	-.023	**.536**	.135	-.257
	Sig. (2-tailed)	.833	.943	.072	.676	.420
	N	12	12	12	12	12

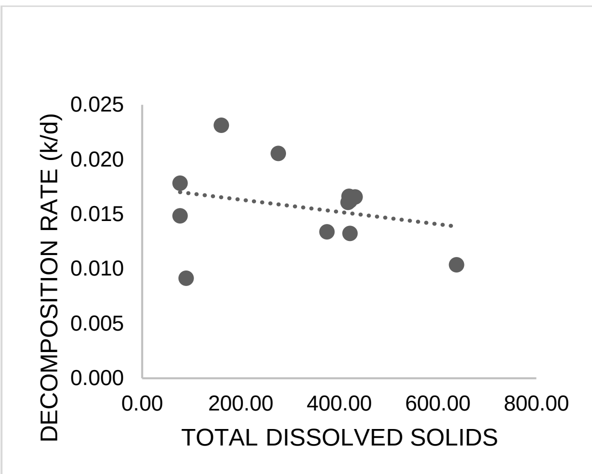
Figure 4: Relationship between decomposition rate and physicochemical parameters



Article DOI: https://doi.org/10.37284/eajenr.7.2.2285







DISCUSSION

Decomposition Rates in the degraded and semi-intact wetlands

This study established that there is a significant difference ($p < 0.001$) in the rates of decomposition between the degraded and semi-intact wetlands. Lubigi wetland recorded a higher decomposition rate (k = 0.20) than Nambigirwa wetland (k = 0.015). Coefficients for plant materials can vary from k = 0.0001 - 4.0 d^{-1} when compared to published values. However, wetland ecosystems usually display values at the lower end of this range (Ruppel et al. 2004). The decay rates calculated for the Lubigi wetland (k = 0.021 kd^{-1}) were comparable to those found by Ruppel and his co-authors in their 2004 study (k = 0.022-0.0245 kd^{-1}). Nevertheless, decay coefficients from other studies in wetland areas (k = 0.00057-0.0024 kd^{-1}) tended to be lower than the values obtained in this study. Throughout the experimental phase, the wetlands underwent a cycle of inundation and aeration caused by a change from dry to wet season, and this could have led to accelerated decomposition. According to Mackintosh, (2015), fluctuations in storm water levels over time can significantly impact the inundation patterns of disturbed wetlands, mainly those with established channels, and thus can affect the decomposition rate. Hydrology marked by periods of wetting and drying increases the rates of leaf decomposition in wetlands by sustaining moisture for microbes that are heterotrophic and therefore preventing anaerobic conditions that hinder biological activity (Fuell et al. 2013; Middleton 2020).

According to a Clarkson et al. (2013) study, anthropogenic activities, such as urban runoff, can further intensify the breakdown rates. Decomposition in Lubigi was accelerated by factors such as wet-dry cycles, increased aeration, and anthropogenic activities like agriculture and urban runoff. Seasonal changes and environmental conditions also influenced decomposition, with higher rates observed during transitions from dry to wet periods. However, the study's short duration and potential overestimation in litter bag experiments should be considered when interpreting the results. However, using small mesh sizes (2 mm) in this study should minimise this overestimation since even the most decomposed samples had leaf fragments significantly more significant than this size.

The rapid decay rates observed in this study can be attributed to the short duration, which only captured the initial stages of decomposition, the timing of the study during a seasonal change from dry to wet, and higher precipitation in the Lubigi wetland, leading to more frequent wet-dry cycles that enhance decomposition. Additionally, factors such as lignin's physical abrasion and leaching from leaves increased leaf litter breakdown rates (Okot-Okumu, 2004). Conversely, Middleton (2020) found that the continuous availability of water within the wetlands may not be as crucial to the decomposition process as well-aerated and moist drawdown conditions, as wetland areas with fluctuating water regimes or having alternative periods of inundation tend to have faster leaf decomposition rates than permanently flooded areas.

Effect of Environmental (Physicochemical) Parameters on the Rate of Decomposition of the Leaf Litter

The decomposition rate increased with conductivity, pH and temperature, yet it slightly decreased with an increase in TDS and Dissolved Oxygen. Korkanç et al. (2022), found that pH indicates wetland water quality across different land uses, which is useful in assessing wetland degradation. Gingerich et al., (2014) suggest that pH ranges in leaf litter decomposition experiments may not have a significant impact on the rate of decomposition. Additionally, acidic environments are not a significant factor to consider when looking at litter decomposition in wetlands (Brumley & Nairn, 2018).

The semi-intact wetland had slightly lower average pH values (6.17-6.72) than the degraded wetland (6.76 -7.12) although still in the neutral range. The lower rates of decomposition with the presence of Total Dissolved Solids (TDS) in water could have been due to increased toxicity which causes salinity affecting the microorganisms (Chen et al., 2021; Peng et al., 2020) and hence reduced breakdown rates. Human activities such as waste dumping and agriculture surrounding the wetlands tend to increase TDS in the water and this could have been the case especially with Lubigi wetland.

Low (Do) dissolved oxygen levels decrease microbial activity, thus impacting leaf breakdown rates (Mackintosh et al., 2015) however, the findings of the study were in line with observations made by Mackintosh (2015), of a negative correlation between dissolved oxygen levels and breakdown rates but differed from the findings of (Ruppel et al., 2004) who observed a positive correlation between dissolved oxygen levels and rates of Decay. Moreover, wetlands with alternating periods of inundation (wet-dry cycles) such as a Lubigi wetland where the experiment was carried out, experienced fluctuations in water levels and hence were more susceptible to external environmental changes that affected the litter decomposition due to their shallower water levels and less vertical stratification than permanently inundated wetlands like Nambigirwa. This was demonstrated in a recent study by Guo et al. (2021).

Additionally, runoff stormwater from impervious surfaces and crop cultivation close to and within the wetlands respectively introduce salts and inorganic chemicals that increase conductivity, which accelerates decay rates due to increased salinity and

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

oxidation reactions. This means that as the salinity in water increases, the conductivity also increases and the higher the salinity and conductivity levels, the lower the dissolved oxygen levels in the water, and this can greatly affect the microorganism populations.

The rate of leaf decay increased with a rise in temperature (r = 0.54). The study results align with the findings of previous studies, such as those conducted by Boyero et al. (2014), Kirwan et al. (2014), Wang et al. (2017) and Hu et al. (2020), which showed that higher temperatures typically lead to faster decomposition rates for litter. However, the results contrast with the findings of Middleton (2020). Faster rates of decomposition with increased temperatures may be attributed to the potential effects of higher temperatures on the enzyme activity of decomposers, as metabolic rates are generally known to increase exponentially with temperature. Further, the increased clearing of wetland vegetation for agriculture opens up the wetlands and hence increases water temperatures.

The mean temperature value (23.25^0C) for the Nambigirwa wetland was slightly higher than that of Lubigi (22.53^0C) and this could be explained by the time when the measurements were made as water parameter measurements were taken mostly in the afternoon when it was slightly hotter due to the remoteness of the place being difficult to access in the morning hours.

This study focused solely on measuring the physicochemical parameters on retrieval days and aggregating the attained values of different spots within the wetlands into one figure giving fewer data values to analyse hence giving a number of outliers. Measuring these parameters across a wider range of values and would have helped reduce the outliers and hence determine their versatility as rapid indicators of wetland health.

CONCLUSIONS

The study evaluated the health of a degraded wetland and a nearly intact wetland through the decomposition process. The study findings indicated that the rates of decomposition were statistically significant between the degraded and semi-intact wetlands. Lubigi (degraded) had a higher mean decomposition rate (compared to the semi-intact Nambigirwa wetland). This was due to the alternating flood regimes caused by the wet-dry cycle, maintaining moisture for the heterotrophic microbes and therefore preventing anaerobic conditions that decrease biological activity. Additionally, the developed areas around Lubigi wetland increased impervious surfaces, leading to heightened storm runoff, temporary flooding, accelerated flow, and faster decomposition due to abrasion.

Intriguingly, the rate of decomposition increased with water parameters such as conductivity, pH, and mainly with temperature but decreased with the presence of TDS and dissolved oxygen. Lower pH inhibits the rate of decomposition. Lubigi wetland recorded slightly higher average values of pH (6.98±0.07) than Nambigirwa wetland (6.50±0.09), although all still in the neutral range, which correlates with a higher rate of decomposition in Lubigi than Nambigirwa (0.025±0.006;0.018±0.005) respectively. Notably, all the measured physicochemical parameters as a whole data set were not significantly correlated with the rate of decomposition.

The National Water and Sewerage Corporation (NWSC) and the National Environment Management Authority must work together to conduct routine water quality tests in all wetlands, especially those in urban areas, not just at sewerage plants established within wetlands. This will enable them to acquire data sets for comparison with the water quality standards/guidelines for ecosystems approved by international agencies such as the UN Environment Programme (UNEP) and the Environmental Protection Agency (EPA).

Through this approach, potential solutions for deviations in physio-chemical parameters can be identified prior to reaching a critical state that could

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

impede the ecosystem's ecological functions. The data collected from routine testing can serve as invaluable indicators for wetland health monitoring, allowing wetland officers to maintain a proactive stance in preserving the wetlands' vitality.

The results of the study enhance our understanding of the physical and biological processes involved in the breakdown of leaf litter in urban wetlands. Such insights will support wetland health monitoring, inform conservation and restoration efforts for these delicate ecosystems. However, the study's statistical power was limited by a small sample size, reducing the ability to detect significant relationships and true effects. Future research should consider increasing the sample size to improve the robustness and generalizability of the findings, making the conclusions more reliable and applicable to a broader context.

A limitation to the study is that it was possible that the time of year when the study was conducted played a role in the results. Conducting the study during a change in season from dry to wet (wet-dry cycles) may have resulted in higher rates of decomposition due to the alternating between flooded and aerobic conditions, which increases breakdown rates. Lubigi wetland area experienced more precipitation volumes than the Nambigirwa study area hence an increase in alternation of the period of inundation at Lubigi which led to increased decay rates. Additionally, the type of litter (*Pennisetum purpureum*) used in the study could have influenced the decay rates. Using green leaves that were air dried instead of naturally senesced leaves tends to result in more significant dry biomass loss due to high levels of leaching.

ACKNOWLEDGEMENTS

We thank the Pan African University Life and Earth Sciences Institute (including Health and Agriculture), Ibadan, Nigeria for providing support, advice and MWE, Wetlands Department officers for providing information regarding the wetlands' status, Wakiso District wetland officers for granting access and Mr. Ntege David for assisting with the field and laboratory work.

Funding for this research was provided by the African Union Commission through the Pan African University Life and Earth Sciences Institute (including Health and Agriculture), Ibadan, Nigeria.

REFERENCES

Adeeyo, A. O., Ndlovu, S. S., Ngwagwe, L. M., Mudau, M., Alabi, M. A., & Edokpayi, J. N. (2022). Wetland Resources in South Africa: Threats and Metadata Study. In Resources (Vol. 11, Issue 6). MDPI. https://doi.org/10.3390/resources11060054

Aerts, R. (1997). Climate, Leaf Litter Chemistry and Leaf Litter Decomposition in Terrestrial Ecosystems: A Triangular Relationship. Oikos, 79(3), 439. https://doi.org/10.2307/3546886

Arroita, M., Aristi, I., Flores, L., Larrañaga, A., Díez, J., Mora, J., Romaní, A. M., & Elosegi, A. (2012). The use of wooden sticks to assess stream ecosystem functioning: Comparison with leaf breakdown rates. Science of the Total Environment, 440, 115–122. https://doi.org/10.1016/j.scitotenv.2012.07.090

Ayanlade, A., & Proske, U. (2015). Assessing wetland degradation and loss of ecosystem services in the Niger Delta, Nigeria. Marine and Freshwater Research, 67(6), 828-836.

Bai, Junhong & Cui, Baoshan & Cao, Huicong & Li, Ainong & Zhang, Baiyu. (2013). Wetland Degradation and Ecological Restoration. The Scientific World Journal. 2013. 523632. 10.1155/2013/523632.

Benfield, E. F., Fritz, K. M., & Tiegs, S. D. (2017). Leaf-Litter Breakdown. Methods in Stream Ecology: Third Edition, 2(December), 71–82. https://doi.org/10.1016/B978-0-12-813047-6.00005-X

 |

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Boyero, L., Pearson, R. G., Gessner, M. O., & Dudgeon, D. (2015). Leaf-litter breakdown in tropical streams: is variability the norm? 34(May 2014), 759– 769. https://doi.org/10.1086/681093.

Brumley, J., & Nairn, R. (2018). Litter Decomposition Rates in Six Mine Water Wetlands and Ponds in Oklahoma. Wetlands, 38(5), 965– 974. https://doi.org/10.1007/s13157-018-1049-y

Charles. (2019). Wetland degradation and carbon sequestration potential – a case of Lubigi wetland, Uganda [Master's thesis]. https://kyuspace.kyu.ac.ug/handle/20.500.12504/808

Chen, W., Wang, J., Cao, X., Ran, H., Teng, D., Chen, J., He, X., & Zheng, X. (2021). Possibility of using multiscale normalized difference vegetation index data for the assessment of total suspended solids (TSS) concentrations in surface water: A specific case of scale issues in remote sensing. Environmental Research, 194(November 2020). https: //doi.org/10.1016/j.envres.2020.110636

Clarkson, B.R., Ausseil, A.E., Gerbeaux, P., & Dymond, J.R. (2013). Wetland ecosystem services.Cook, A. R. (2014). Loyola eCommons Environmental Drivers of Leaf Breakdown Rate in an Urban Watershed.

Crecious, H., & Lazarus, C. (2013). Human perceptions on degradation of wetland ecosystems: the case of Magwenzi Wetland in Chivi District; Zimbabwe. Greener Journal of Geology and Earth Sciences, 1(1), 013-022.

Das, A., & Basu, T. (2020). Assessment of peri-urban wetland ecological degradation through importance-performance analysis (IPA): A study on Chatra Wetland, India. Ecological Indicators, 114, 106274. https://doi.org/10.1016/j.ecolind.2020.106274

De, M., Medda, S., & Dey, S. R. (2018). Ecological Health of Wetland Ecosystem: An overview. International Journal of Experimental Research and Review, 17(November), 20–29. https://doi.org/10.52756/ijerr.2018.v17.005

Dodds, W. and Whiles, M. (2010) Freshwater Ecology: Concepts and Environmental Applications of Limnology. 2nd Edition, Elsevier, Amsterdam, 330-333.

Egoh, B. N., O'Farrell, P. J., Charef, A., Josephine Gurney, L., Koellner, T., Nibam Abi, H., Egoh, M., & Willemen, L. (2012). An African account of ecosystem service provision: Use, threats and policy options for sustainable livelihoods. Ecosystem Services, 2, 71–81. https://doi.org/10.1016/j.ecoser.2012.09.004

Entrekin, S. A., Fuell, A. K., Entrekin, S. A., Scott, G., & Owen, S. K. (2015). Drivers of Leaf Decomposition in Two Wetland Types in the Arkansas River Valley, USA. May. https://doi.org/10.1007/s13157-013-0468-z

Fuell, A. K., Entrekin, S. A., Owen, G. S., & Owen, S. K. (2013). Drivers of leaf decomposition in two wetland types in the Arkansas River valley, U.S.A. Wetlands, 33(6), 1127–1137. https://doi.org/10.1007/s13157-013-0468-z

Gingerich, R. T. (2010). Plant litter decomposition in mitigated and reference wetlands. West Virginia University.

Gingerich, R. T., & Anderson, J. T. (2011). Litter decomposition in created and reference wetlands in West Virginia, USA. Wetlands Ecology and Management, 19(5), 449–458. https://doi.org/10.1007/s11273-011-9228-0

Gingerich, R. T., Merovich, G., & Anderson, J. T. (2014a). Influence of environmental parameters on litter decomposition in wetlands in West Virginia, USA. Journal of Freshwater Ecology, 29(4), 535– 549. https://doi.org/10.1080/02705060.2014.926463

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Gingerich, R. T., Merovich, G., & Anderson, J. T. (2014b). Influence of environmental parameters on litter decomposition in wetlands in West Virginia, USA. Journal of Freshwater Ecology, 29(4), 535– 549. https://doi.org/10.1080/02705 060.2014.926463

GoU (Government of Uganda), 2016. Uganda Wetland Atlas Volume II, Ministry of Water and Environment, United Nations Environment Programme (UNEP), and the United Nations Development Programme (UNDP), MWE, Kampala. http://www.mwe.org

Guo, Y., Boughton, E. H., & Qiu, J. (2021). Interactive effects of land-use intensity, grazing and fire on decomposition of subtropical seasonal wetlands. Ecological Indicators, 132, 108301. https://doi.org/10.1016/j.ecolind.2021. 108301

Harbourd, H., Barton, J. L., Pearse, A., & Lester, R. E. (2015). Functional indicators of decomposition for monitoring ecosystem health in urban and agricultural wetlands A report prepared for the South Australian Department of Environment, Water and Natural Resources.

Harmon, M. E., Silver, W. L., Fasth, B., Chen, H., Burke, I. C., Parton, W. J., Hart, S. C., & Currie, W. S. (2009). Long-term patterns of mass loss during the decomposition of leaf and fine root litter: An intersite comparison. Global Change Biology, 15(5), 1320- 1338. https://doi.org/10. 1111/j.1365-2486.2008.01837.x

Hedman, A. (2019). Effects of land use on wetland carbon storage and ecosystem services in the tropics A first estimation investing rural wetlands in central and eastern Uganda. Umea Universitet, 73.

Jabbar, M. A. (Mohammad A., International Livestock Research Institute., International Development Research Centre (Canada), & ILRI-IDRC Planning Workshop on Agro-Ecosystem Health (1998: ILRI, A. A. (2000). Agro-ecosystems, natural resources management, and human health related research in East Africa: proceedings of an IDRC-ILRI international workshop held at ILRI, Addis Ababa Ethiopia, 11-15 May 1998. International Development Research Centre.

Kakuru, W., Turyahabwe, N., & Mugisha, J. (2013). Total economic value of wetlands products and services in Uganda. The Scientific World Journal, 2013. https://doi.org/10.1155/2013/19 2656

Kayima, J. K., Mayo, A. W., & Nobert, J. K. (2018). The Fate of Nitrogen and Faecal Coliform in the Lubigi Wetland in Uganda. In Tanzania Journal of Engineering and Technology (Vol. 37, Issue 2).

Kirwan, M. L., Guntenspergen, G. R., & Langley, J. A. (2014). Temperature sensitivity of organic-matter decay in tidal marshes. Biogeosciences, 11(17), 4801–4808. https://doi.org/10.5194/bg-11-4801-2014

Kometa, S. S. (2018). Urban Development and its Implications on Wetland Ecosystem Services in Ndop, Cameroon. 7(1), 21–36. https://doi.org/10.5296/emsd.v7i1.12141

Langan, C., Farmer, J., Rivington, M., Novo, P., & Smith, J. U. (2019). A wetland ecosystem service assessment tool; Development and application in a tropical peatland in Uganda. Ecological Indicators, 103, 434–445. https://doi.org/10.1016/j.ecolind.2019.04.019

Lu, H. (2023). Urbanization-driven anthropogenic and environmental factors shape soil dissolved organic matter in mangrove ecosystems. Ecosystem Health and Sustainability, 1–14. https://doi.org/10.34133/ehs.0154

Lu, Y., Wang, R., Zhang, Y., Su, H., Wang, P., Jenkins, A., ... & Squire, G. (2015). Ecosystem health towards sustainability. Ecosystem Health and Sustainability, 1(1), 1-15.

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Mackintosh, T. J., Davis, J. A., & Thompson, R. M. (2015). Impacts of multiple stressors on ecosystem function: Leaf decomposition in constructed urban wetlands. Environmental Pollution, 1–12. https://doi.org/10.1016/j.envpol.2015.08.038

Mackintosh, T. J., Davis, J. A., & Thompson, R. M. (2016). Impacts of multiple stressors on ecosystem function: Leaf decomposition in constructed urban wetlands. Environmental Pollution, 208(August), 221–232. https://doi.org/10.1016/j.envpol.2015.08.038

Mandishona, E., & Knight, J. (2022). Inland wetlands in Africa: A review of their typologies and ecosystem services. Progress in Physical Geography, 46(4), 547–565. https://doi.org/10.1177/03091333221075328

Martínez, A., Larrañaga, A., Pérez, J., Descals, E., & Pozo, J. (2014). Temperature affects leaf litter decomposition in low-order forest streams: Field and microcosm approaches. FEMS Microbiology Ecology, 87(1), 257–267. https://doi.org/10.1111/1574-6941.12221

Meli, P., Rey Benayas, J. M., Balvanera, P., & Ramos, M. M. (2014). Restoration Enhances Wetland Biodiversity and Ecosystem Service Supply, but Results Are Context-Dependent: A Meta-Analysis. PLOS ONE, 9(4), e93507. https://doi.org/10.1371/journal.pone.0093507

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

Mitsch, W.J. and Gosselink, J.G. (2015) Wetlands. 5th Edition, John Wiley & Sons, Inc., Hoboken

Mitchell, S. A. (2013). The status of wetlands, threats and the predicted effect of global climate change: The situation in Sub-Saharan Africa. In Aquatic Sciences (Vol. 75, Issue 1, pp. 95–112). https://doi.org/10.1007/s00027-012-0259-2

Mitsch, W. J., Bernal, B., Hernandez, M. E., Mitsch, W. J., Bernal, B., & Ecosystem, M. E. H. (2015). Ecosystem services of wetlands. International Journal of Biodiversity Science, Ecosystem Services & Management, 11(1), 1–4.https://doi.org/10.1080/21513732.2015.1006250

Nayak, A., & Bhushan, B. (2022). Wetland ecosystems and their relevance to the environment: importance of wetlands. In Handbook of research on monitoring and evaluating the ecological health of wetlands (pp. 1-16). IGI Global.

Nsubuga, F. N. W., Namutebi, E. N., & Nsubuga-Ssenfuma, M. (2014). Water Resources of Uganda: An Assessment and Review. Journal of Water Resource and Protection, 06(14), 1297– 1315. https://doi.org/10.4236/jwarp.2014.614120

O'Brien, A., Townsend, K., Hale, R., Sharley, D., & Pettigrove, V. (2016). How is ecosystem health defined and measured? A critical review of freshwater and estuarine studies. Ecological Indicators, 69, 722-729.

Okot-Okumu, J. (2004). Primary production and decomposition of Loudetia phragmitoides (A. Peter) in the littoral wetland of a small satellite lake (L. Nabugabo, Uganda). African Journal of Ecology, Supplement, 42(1), 108–113. https://doi.org/10.1111/j.1365-2028.2004.00471.x

Osewe, I., Hălălișan, A. F., Talpă, N., & Popa, B. (2023). Critical Analysis of Payments for Ecosystem Services: Case Studies in Kenya, Uganda and Tanzania. Forests, 14(6). https://doi.org/10.3390/f14061209

Gideon, O.J., & Bernard, B. (2018). Effects of Human Wetland Encroachment on the

Degradation of Lubigi Wetland System, Kampala City Uganda. *Environment and Ecology Research*.

Peng, J., Kumar, K., Gross, M., Kunetz, T., & Wen, Z. (2020). Removal of total dissolved solids from wastewater using a revolving algal biofilm reactor. Water Environment Research, 92(5), 766–778. https://doi.org/10.1002/wer.1273

Perrings, C., Naeem, S., Ahrestani, F.S., Bunker, D.E., Burkill, P.H., Canziani, G.A., Elmqvist, T., Ferrati, R., Fuhrman, J.A., Jaksic, F.M., Kawabata, Z., Kinzig, A., Mace, G.M., Milano, F., Mooney, H., Prieur-Richard, A., Tschirhart, J., & Weisser, W.W. (2010). Ecosystem Services for 2020. Science, 330, 323 - 324.

Petraglia, A., Cacciatori, C., Chelli, S., Fenu, G., Calderisi, G., Gargano, D., Abeli, T., Orsenigo, S., & Carbognani, M. (2019). Litter decomposition: effects of temperature driven by soil moisture and vegetation type. Plant and Soil, 435(1–2), 187–200. https://doi.org/10.1007/s11104-018-3889-x

Rapport, D. J., Costanza, R., & McMichael, A. J. (1998). Assessing ecosystem health. Trends in ecology & evolution, 13(10), 397-402.

Ramsar Convention Secretariat (2013). The Ramsar Convention Manual: A Guide to the Convention on Wetlands (Ramsar, Iran, 1971) (6th ed.). Gland: Ramsar Convention Secretariat.

Ruppel, A., Ruppel, R. E., Setty, K. E., & Wu, M. (2004). Decomposition Rates of Typha Spp. in Northern Freshwater Wetlands over a Stream-Marsh-Peatland Gradient Item Type Article Decomposition Rates of Typha Spp. in Northern Freshwater Wetlands over a Stream-Marsh-Peatland Gradient. http://hdl.handle.net/20.500.12648/1254

Sampaio, A., Rodríguez-González, P., Varandas, S., Cortes, R. M., & Ferreira, M. T. (2008). Leaf litter decomposition in western Iberian forested wetlands: Lentic versus lotic response. Limnetica, 27(1), 93–106. https://doi.org/10.23818/limn.27.08

Schuyt, K. D. (2005). Economic consequences of wetland degradation for local populations in Africa. 53, 177–190. https://doi.org/10.1016/j.ecolecon.2004.08.003

Song, Y. Bin, Zhou, M. Y., Qin, Y. L., Cornelissen, J. H. C., & Dong, M. (2021). Nutrient effects on aquatic litter decomposition of free-floating plants are species dependent. Global Ecology and Conservation, 30(May), e01748. https://doi.org/10.1016/j.gecco.2021.e01748

Song, S., Hu, X., Zhu, J., Zheng, T., Zhang, F., Ji, C., & Zhu, J. (2021). The decomposition rates of leaf litter and fine root and their temperature sensitivities are influenced differently by biotic factors. Plant and Soil, 461(1–2), 603–616. https://doi.org/10.1007/s11104-021-04855-7

Suseela, V. (2019). Potential roles of plant biochemistry in mediating ecosystem responses to warming and drought. In Ecosystem Consequences of Soil Warming: Microbes, Vegetation, Fauna and Soil Biogeochemistry. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813493-1.00005-3

Tenkiano, N. S. D., & Chauvet, E. (2018). Leaf litter decomposition in Guinean savannah streams. Inland Waters, 8(4), 413– 421. https://doi.org/10.1080/20442041.2018.1487175

Tiegs, S. D., Clapcott, J. E., Griffiths, N. A., & Boulton, A. J. (2013). A standardized cotton-strip assay for measuring organic-matter decomposition in streams. Ecological Indicators, 32, 131–139. https://doi.org/10.1016/j.ecolind.2013.03.013

Turyahabwe, N., Kakuru, W., Tweheyo, M., & Tumusiime, D. M. (2013). Contribution of wetland resources to household food security in

Article DOI: https://doi.org/10.37284/eajenr.7.2.2285

Uganda. 2(1), 1. https://doi.org/10.1186/2048-7010-2-5

Wang, X., Xu, Z., Lü, X., Wang, R., Cai, J., Yang, S., Li, M. H., & Jiang, Y. (2017). Responses of litter decomposition and nutrient release rate to water and nitrogen addition differed among three plant species dominated in a semi-arid grassland. Plant and Soil, 418(1–2), 241–253. https://doi.org/10.1007/s11104-017-3288-8

Xie, Y., Xie, Y., & Xiao, H. (2019). Differential responses of litter decomposition to climate between wetland and upland ecosystems in China. Plant and Soil, 440(1–2), 1–9. https://doi.org/10.1007/s11104-019-04022-z

Yarwood, S. A. (2018). The role of wetland microorganisms in plant-litter decomposition and soil organic matter formation: A critical review. FEMS Microbiology Ecology, 94(11). https://doi.org/10.1093/femsec/fiy175